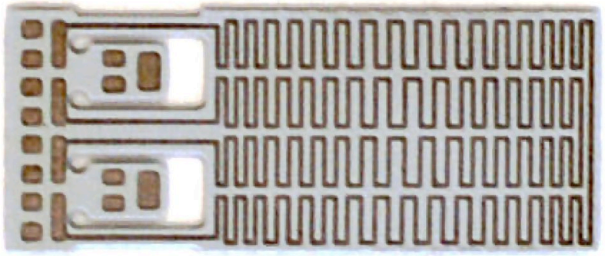
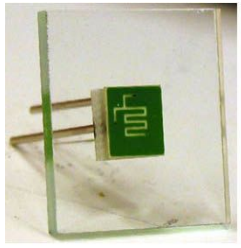
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

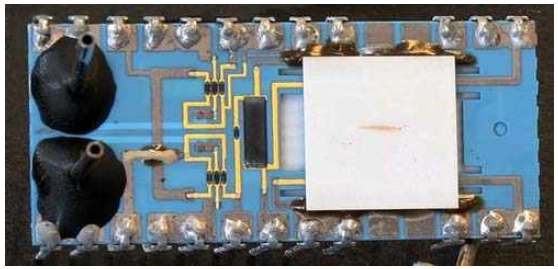
3D structuration of LTCC and related technologies for thermal management and microfluidics

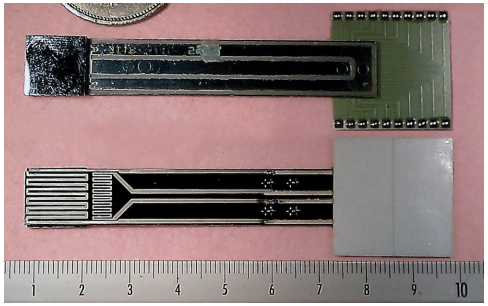
Thomas Maeder[1], Conor Slater[1], Bo Jiang[1,2], Fabrizio Vecchio[1], Caroline Jacq[1], and Peter Ryser[1]

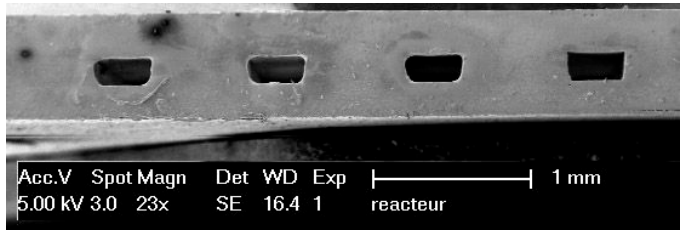
EPFL-LPM[1] & EPFL-LC[2]

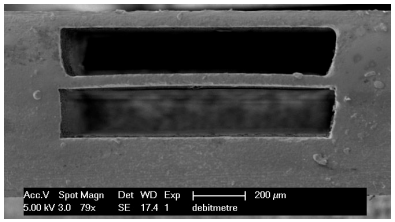












MIDEM

Outline

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

1. Introduction
2. Processing for 3D
3. Materials formulation
4. Conclusion & outlook

Outline (1)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

1. **Introduction**
   - **Our lab**
   - **Thick-film & LTCC**
2. **Processing for 3D**
3. **Materials formulation**
4. **Conclusion & outlook**

EPFL - Swiss Federal Institute of Technology

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

EPFL
École Polytechnique Fédérale de Lausanne

One of the two polytechnical schools in Switzerland

10’000	Population on the campus
6’000	Students
3’500	Collaborators
1’400	PhD. Students
250	Professors
550	MSFr budget / year
70	Companies on site
10	New start-ups / year

EPFL - Faculties - Engineering

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

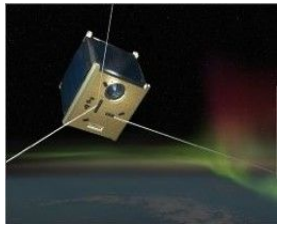
- **SB:** School of basic sciences
  - Chemistry, mathematics and physics
- **SV:** School of life sciences
  - Genomics, neurosciences, …
- **ENAC:** School of civil + environmental engineering & architecture
  - Architecture, civil engineering, environmental sciences and technologies
- **I&C:** School of informatics and communications
  - Fundamental & applied computer science, communication systems
- **STI: School of engineering**
  - Electricity, materials, mechanical engineering, biomedical engineering, **microtechnology**

EPFL-STI - School of Engineering

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- **IMX:** Institute of materials science & engineering
  - Metals, ceramic, polymers, composites, poweders, bio-/nanomaterials,…
- **IEL:** Institute of electrical engineering
  - Circuits & devices, power & energy, telecom, computers…
- **IGM:** Institute of mechanical engineering
  - Solid + fluid mechanics, heat + mass transfer, biomechanics, control…
- **IBI:** Institute of bioengineering
  - Biology, chemistry, biomaterials, … *(with school of life sciences)*
- **IMT: Institute of microengineering**
  - Microsystems, robotics, optics, production, …
  - Inherently multidisciplinary
- *+ several technology centres:*

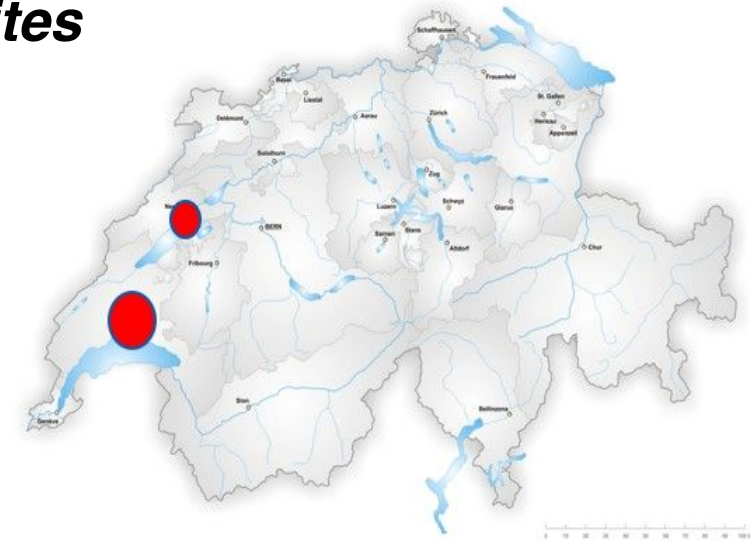
http://imt.epfl.ch


IMT - Locations

The new IMT: 1 Institute on 2 Sites

Lausanne + Neuchâtel Campus



Distance: ~70 km or 45 min

Close collaborations

csem

Hes·so

Haute Ecole Spécialisée de Suisse occidentale

Industry

http://imt.epfl.ch

LPM - Lab. of microengineering for manufacturing

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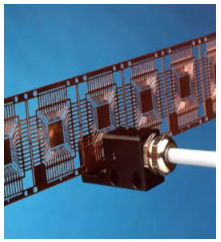
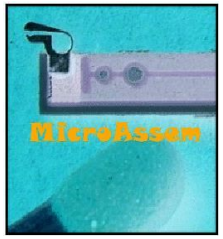
Laboratoire de Production Microtechnique

Vision & μ-Assembly

Director : Prof. J. Jacot

Group head : A. Dufaux

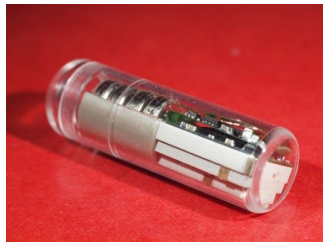




Product design

Director : Prof. P. Ryser

Group head : E. Meurville



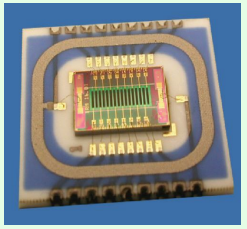
Production strategy

Director : Prof. M.-O. Hongler

Thick-film technology

Director : Prof. P. Ryser

Group head : Th. Maeder



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Topics of LPM thick-film group @ EPFL

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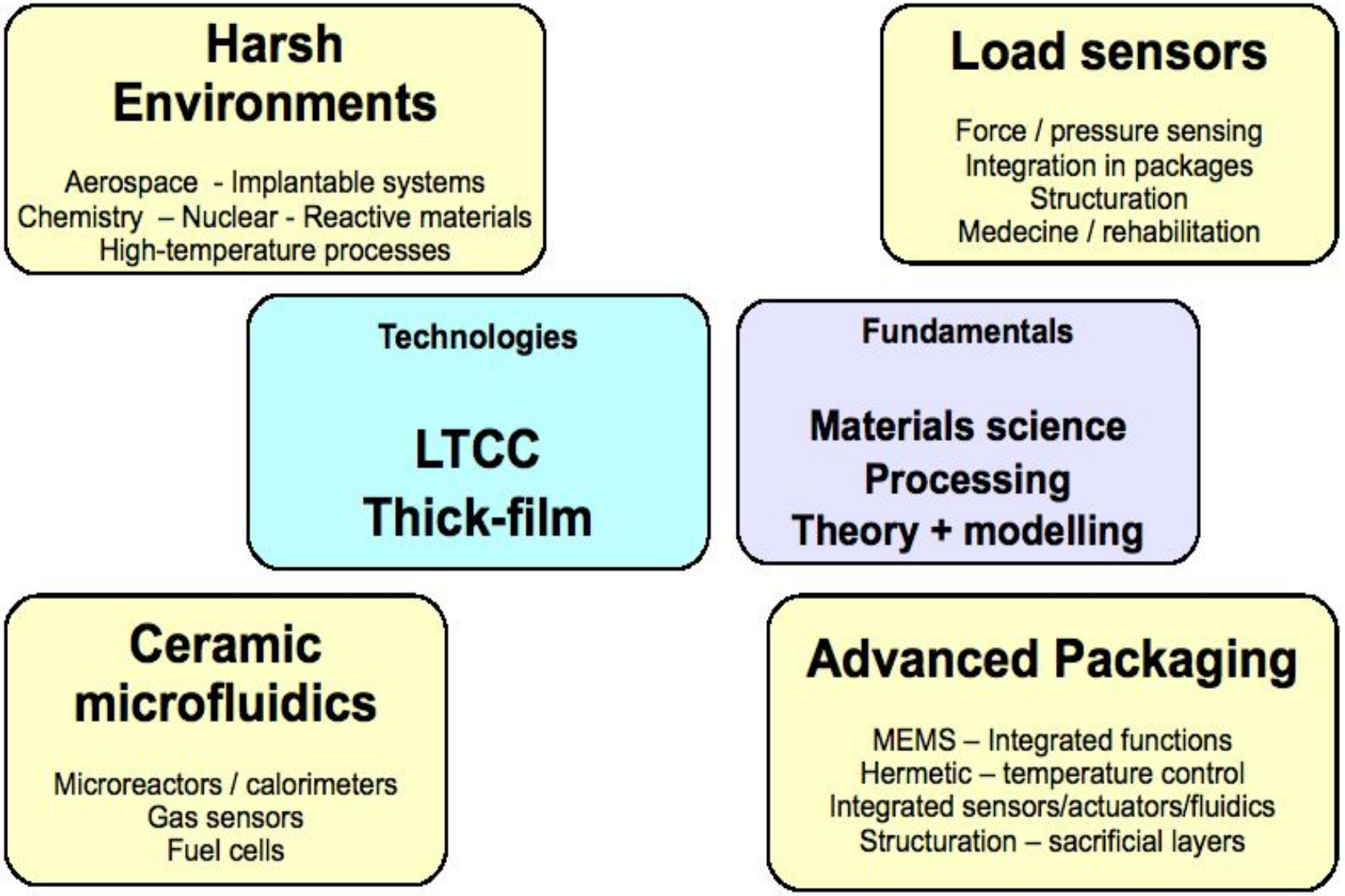

Thick-film technology - introduction

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- **Thick-film circuit : series of layers**
  - Screen-printing of layers with a mask
  - Direct dispensing (prototypes)

- **Each layer comes as a paste:**
  - Functional material (as powder)
  - Organic vehicle: binder + solvent

- **Materials**
  - Conductors
  - Resistors
  - Dielectrics
  - …**and more!**

Thick-film - process flow

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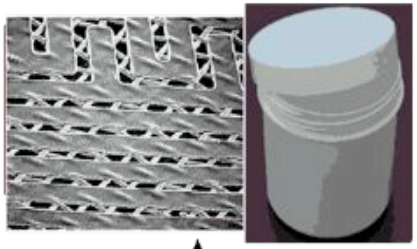
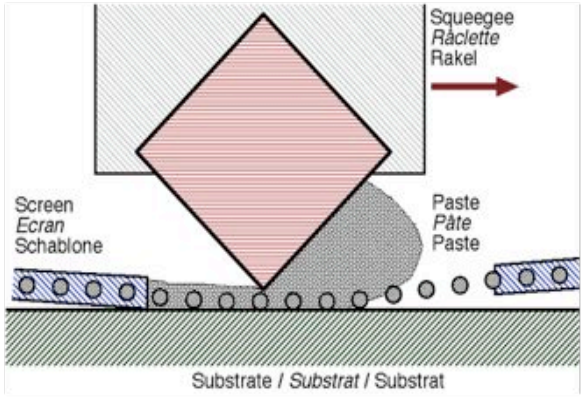
Sequential firing

Substrate
Substrat

1 Screen & paste
Ecran & pâte
Maske & Paste

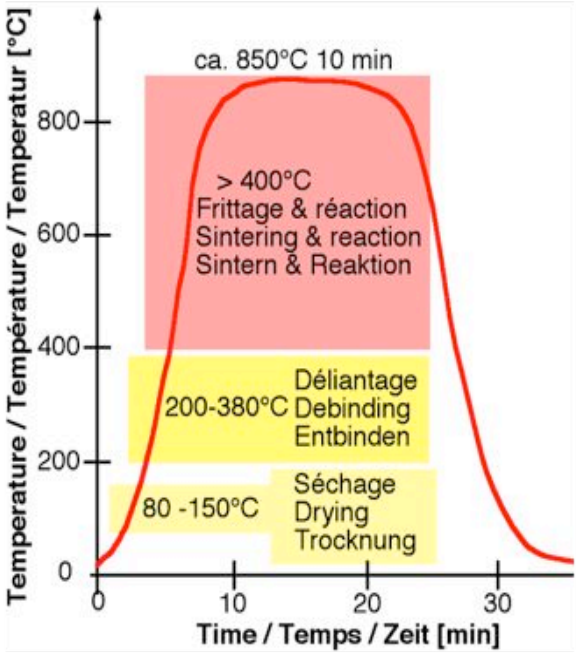


2 Screen printing
Sérigraphie
Siebdruck

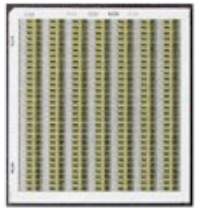


3 Drying
Séchage
Trocknen

ca.
150°C
15 min



4 Firing
Cuisson
Einbrand



Circuit
Schaltung

LTCC - introduction - the material?

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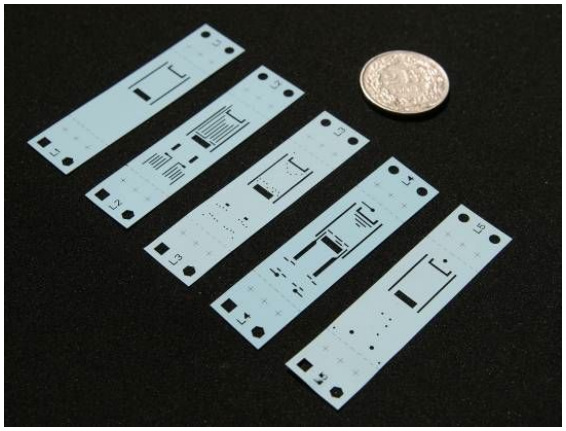
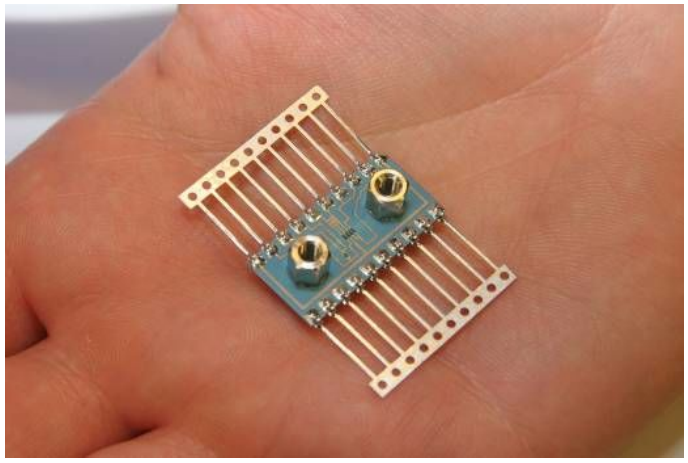
Low-Temperature, Cofired Ceramic

- Sheets of sintered ceramics (blue, white or black)
- You're carrying it unawares (mobile phone, car ignition)
- Relatively new material (<20 yrs)
- Developed for highly integrated electronics

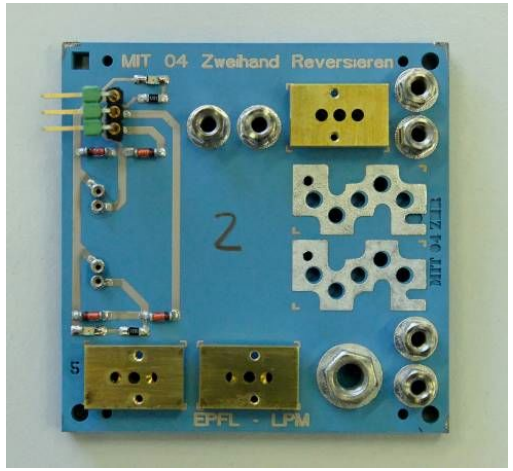


raw sheets of LTTC (micro-reactor)

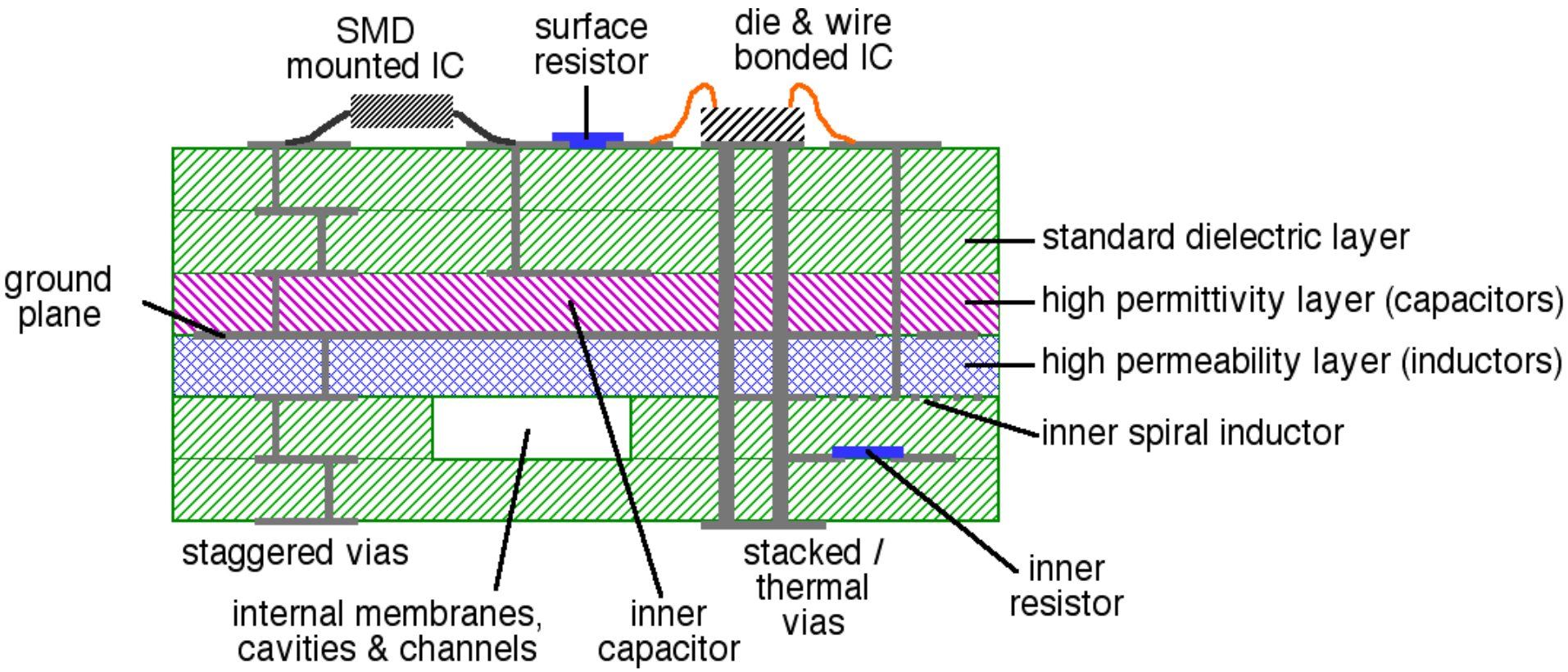


micro-flow sensor assembled

fluidic circuit, management of valves with SMD electronics



3-D structuration of LTCC



LTCC vs. alumina for sensors

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Material	LTCC (DP 951)	Al_2O_3 (96%)	Ratio
Minimal thickness [mm]	0.04	0.17	*0.24*
Short-term strength [MPa]	320	600	*0.53*
10 year strength [MPa]	110	270	*0.41*
Young's modulus [GPa]	110	320	*0.34*
Thermal conductivity [W/m]	3	25	*0.12*
Design strain [ppm]	1'000	800	*1.25*
Flexural sensitivity [kN^{-1}]	5.68	0.11	*53*
Thermal resistance [K/W]	8'333	235	*35*

- LTCC more sensitive
- Good 3D structurability
- Compatibility with standard mounting (SMD)

LTCC - process flow

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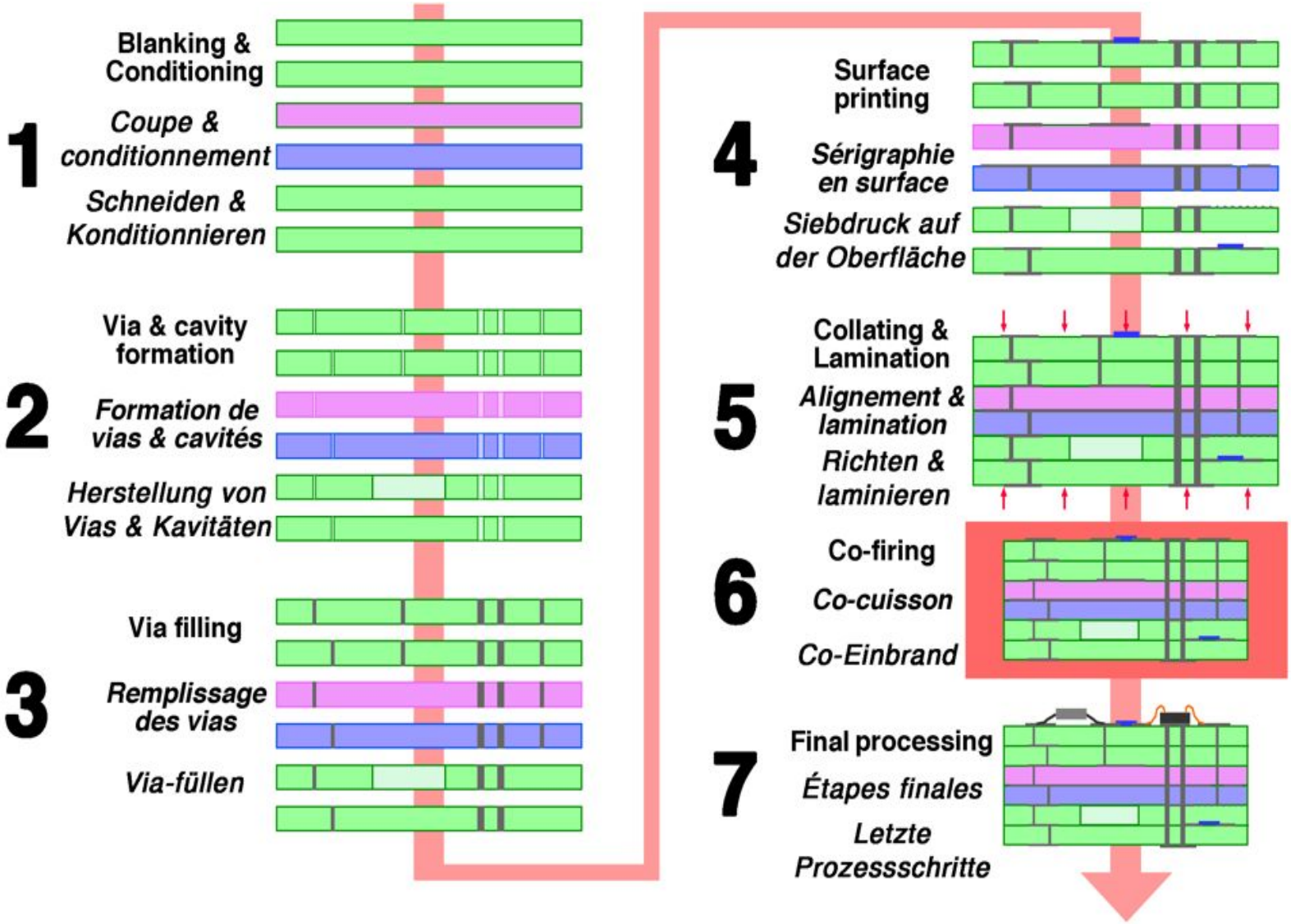
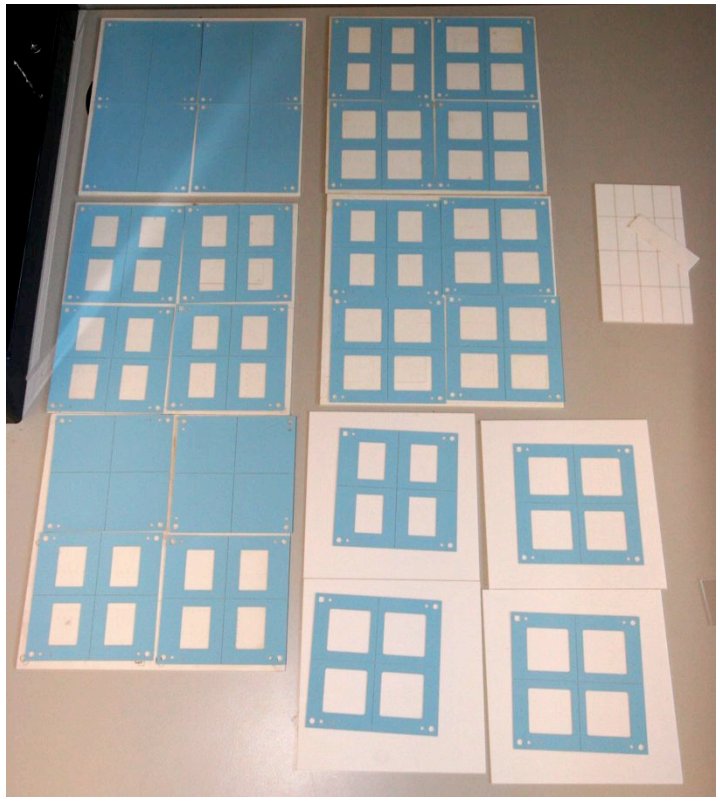
Co-firing



LTCC - principle - 1 & 2

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

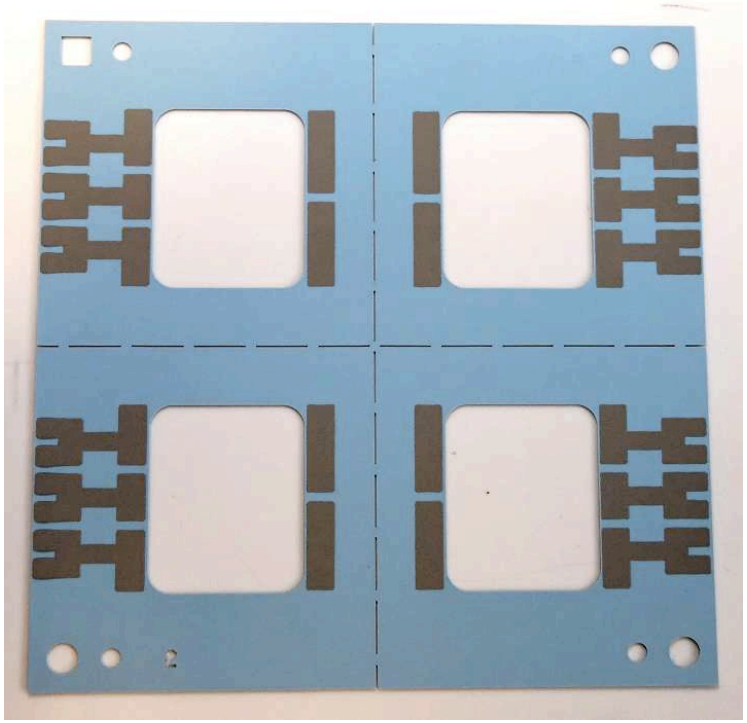
1. Raw sheets easily cut
   (laser, punch tool)
2. Formation of vias & cavities
3. Vias filled for interlayer contacts
4. Layers individually printed
   (multilayer circuits)
5. Stacking & lamination of layers to get
   a 3D structure
6. Firing
   -> sintering, monolithic circuit
7. Individualisation and post-firing
   (assembly by soldering)



LTCC - principle - 3 & 4

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

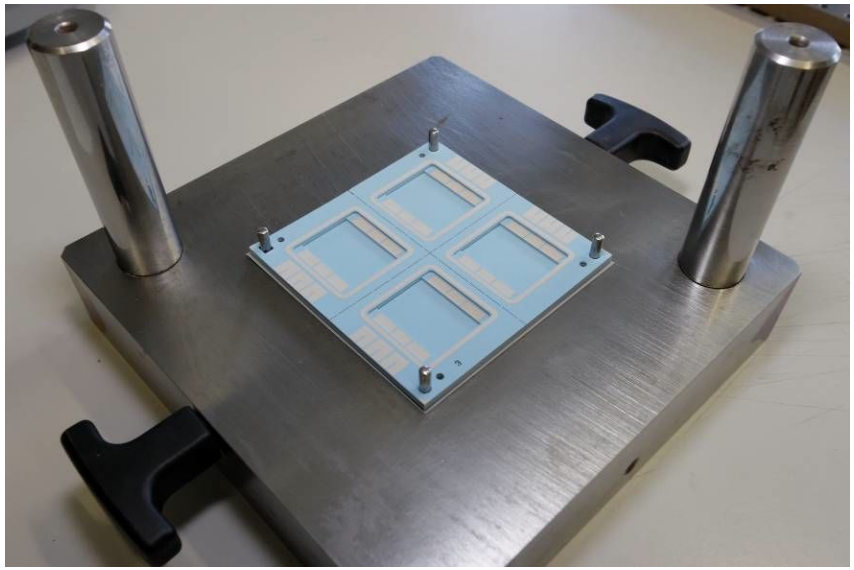
1. Raw sheets easily cut
   (laser, punch tool)
2. Formation of vias & cavities
3. Vias filled for interlayer contacts
4. Layers individually printed
   (multilayer circuits)
5. Stacking & lamination of layers to get
   a 3D structure
6. Firing
   -> sintering, monolithic circuit
7. Individualisation and post-firing
   (assembly by soldering)



LTCC - principle - 5

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

1. Raw sheets easily cut (laser, punch tool)
2. Formation of vias & cavities
3. Vias filled for interlayer contacts
4. Layers individually printed (multilayer circuits)
5. Stacking & lamination of layers to get a 3D structure
6. Firing -> sintering, monolithic circuit
7. Individualisation and post-firing (assembly by soldering)



LTCC - principle - 6

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

1. Raw sheets easily cut
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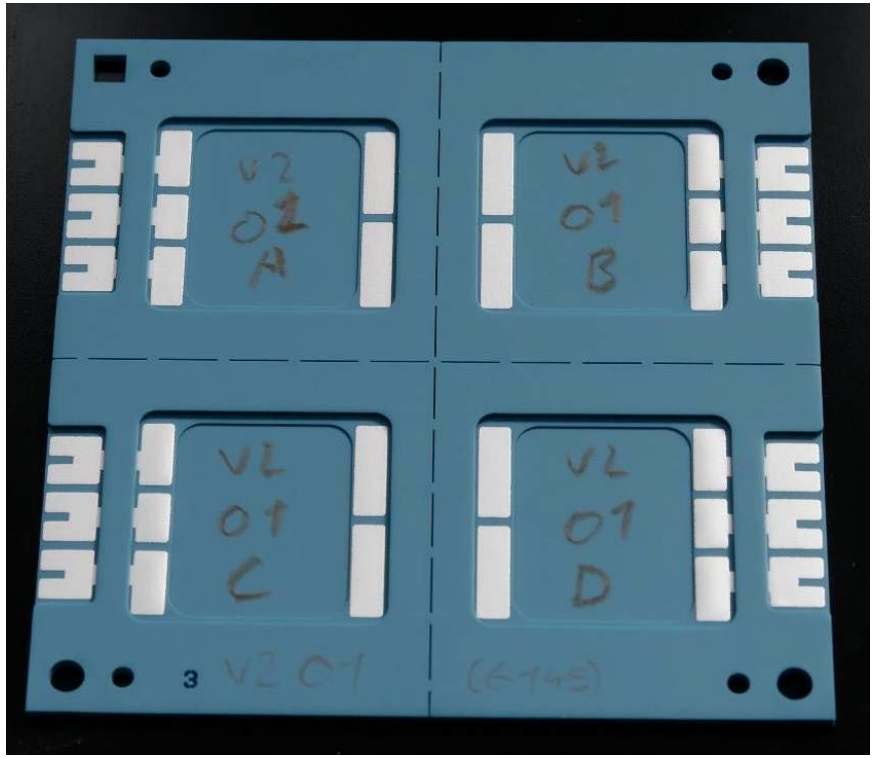
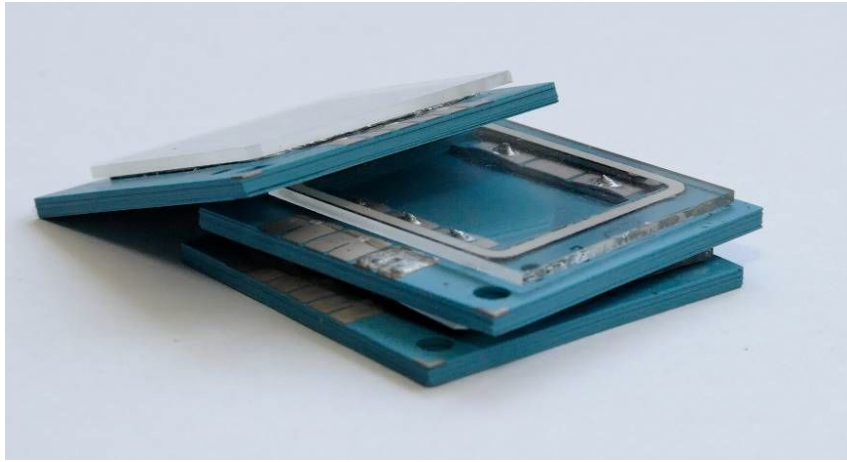
2. Formation of vias & cavities
3. Vias filled for interlayer contacts
4. Layers individually printed
   (multilayer circuits)
5. Stacking & lamination of layers to get
   a 3D structure
6. Firing
   -> sintering, monolithic circuit
7. Individualisation and post-firing
   (assembly by soldering)



LTCC - principle - 7

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

1. Raw sheets easily cut (laser, punch tool)
2. Formation of vias & cavities
3. Vias filled for interlayer contacts
4. Layers individually printed (multilayer circuits)
5. Stacking & lamination of layers to get a 3D structure
6. Firing -> sintering, monolithic circuit
7. Individualisation and post-firing (assembly by soldering)



Outline (2)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

1. Introduction
2. **Processing for 3D**
3. Materials formulation
4. Conclusion & outlook

- **Basic processing for 3D structures**
- **Handling issues**
- **Sacrificial volume materials (SVMs)**
- **Lamination & firing**

LTCC structuration methods

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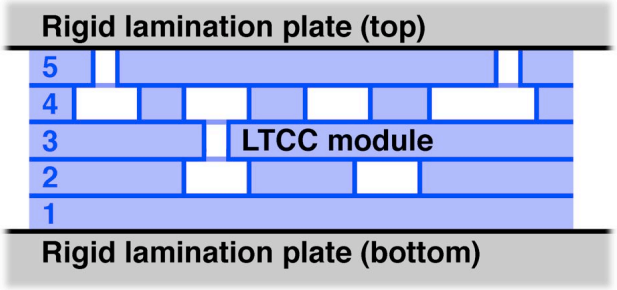
Features

- Vias
- Channels
- Membranes
- Beams

Three lamination routes

1) Cutting & stacking, flat
2) Cutting & stacking, +SVM
3) Structuration by SVM

1



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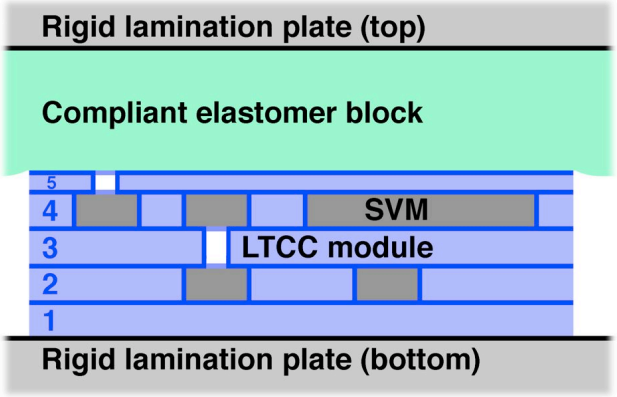

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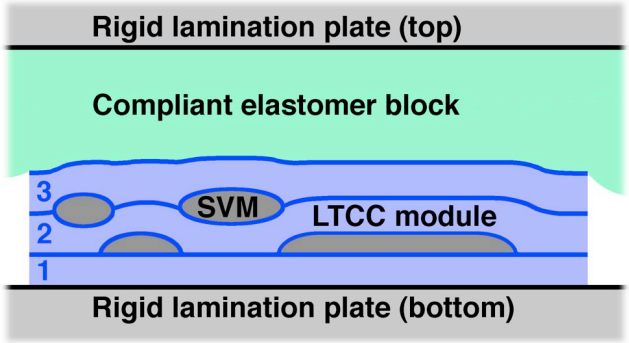
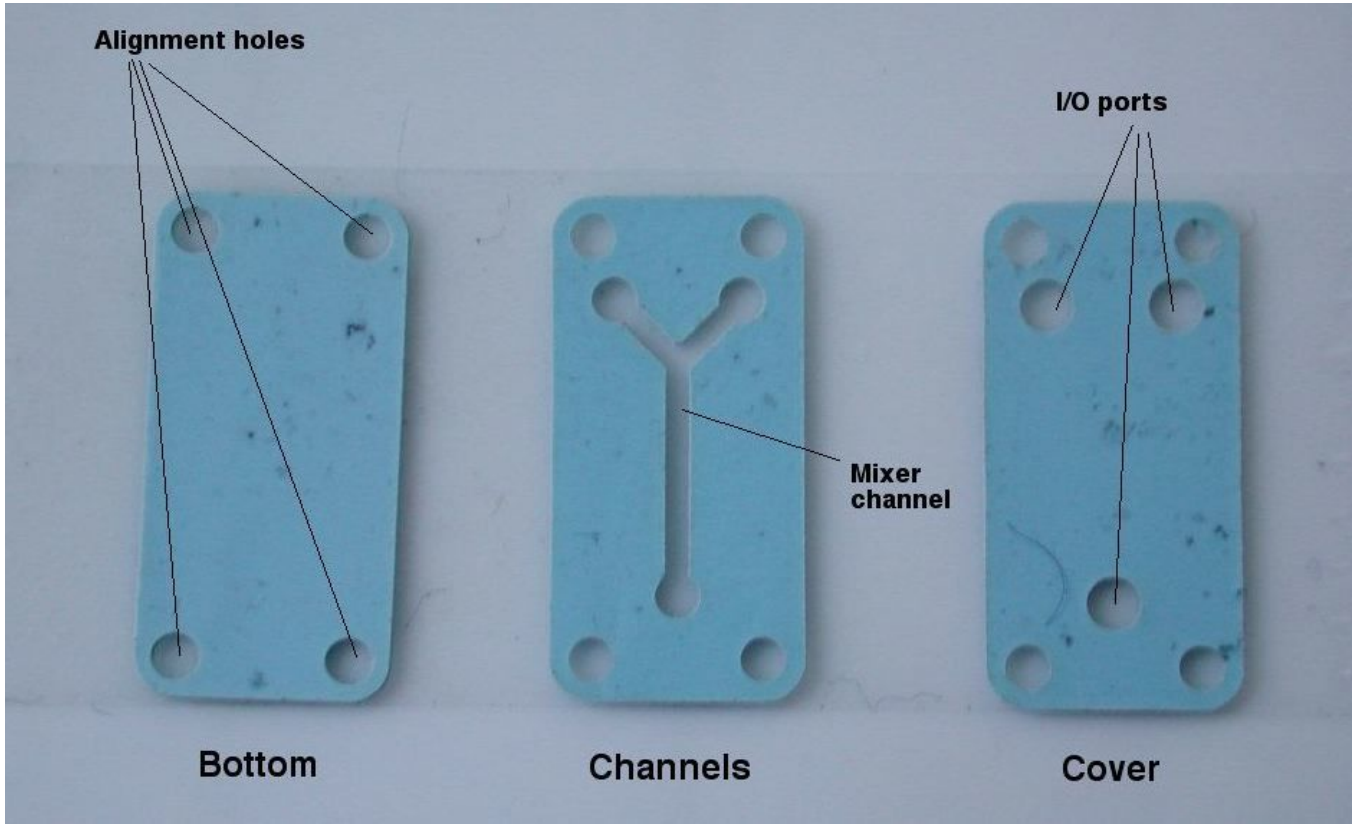


Cutting & stacking LTCC

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Process

1. Cutting
2. Stacking & laminating
3. Firing



A simple LTCC micromixer

Ceramic structuration: microreactor

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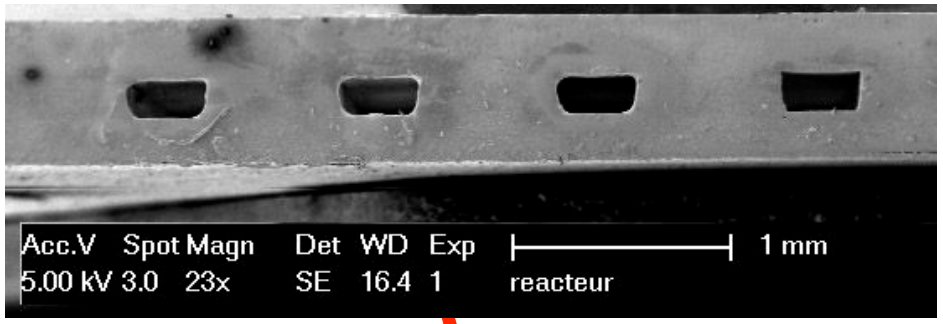
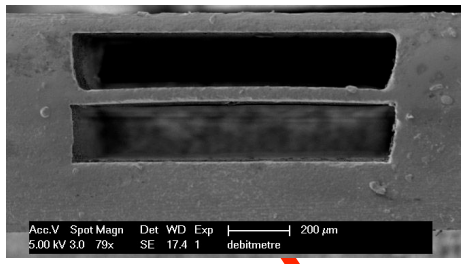
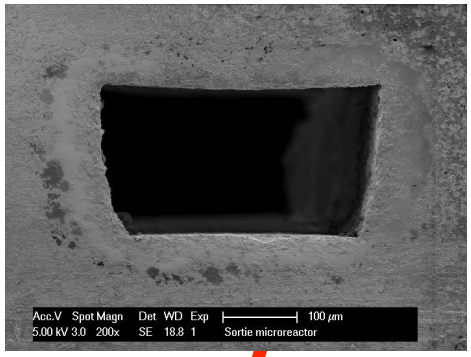
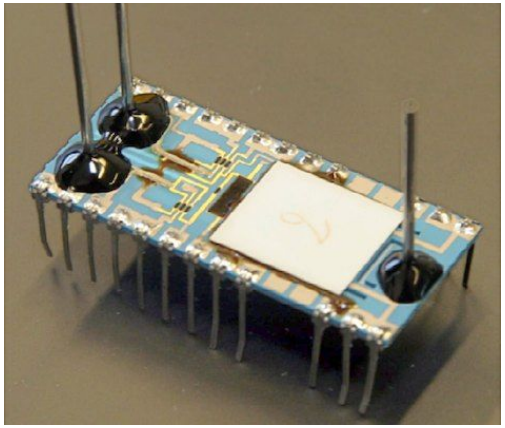
- Complex fluidic circuit (2 layers + membranes)
- Flow sensors
- Heaters
- Channels in support posts
- …



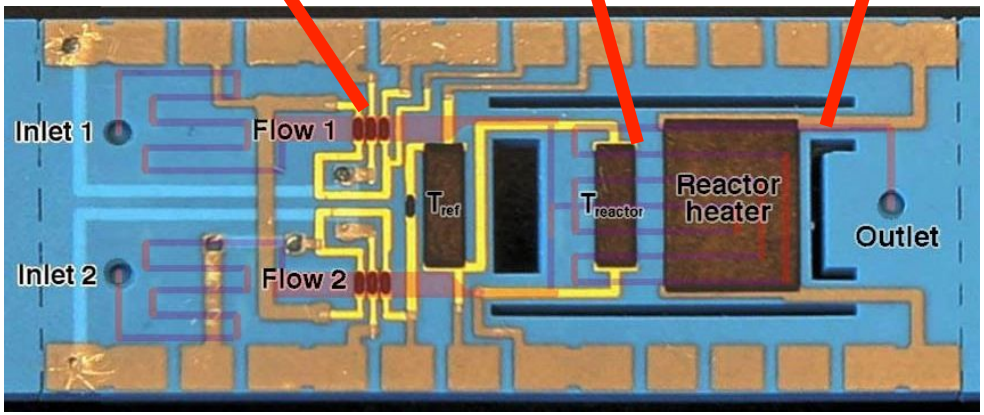






Complete device

LTCC module + fluidic circuit



LTCC μ-SOFC test platform

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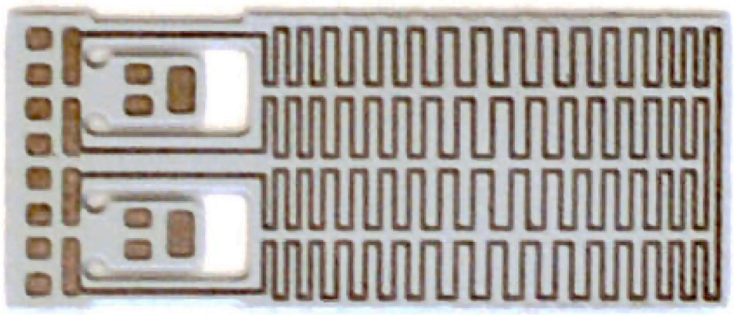
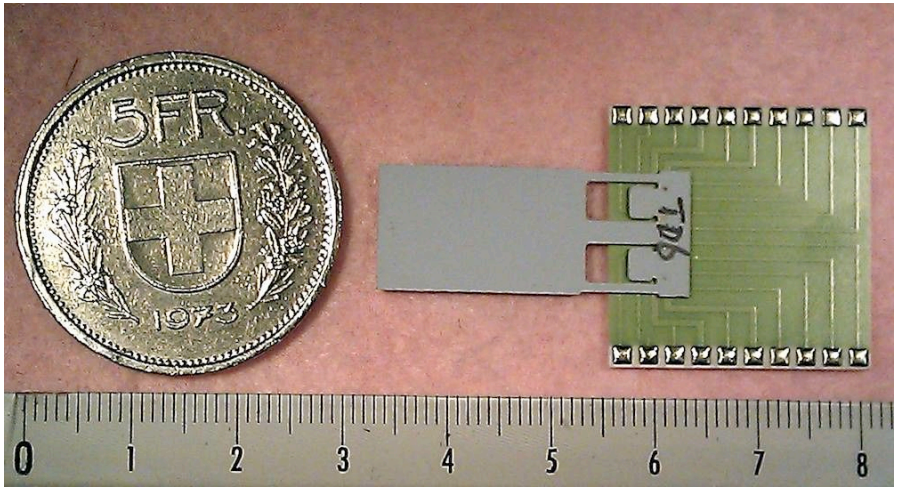
- Thermal decoupling by slender bridges
- Electrical (bottom) & fluidic (top) connections
- Heating & temperature control by Pt meanders
- SMD-soldered to thick-film base for easy connections & cooling of "cold" side



LTCC μ-SOFC test platform

Pt track



Platform mounted onto base

Fluidic multisensor

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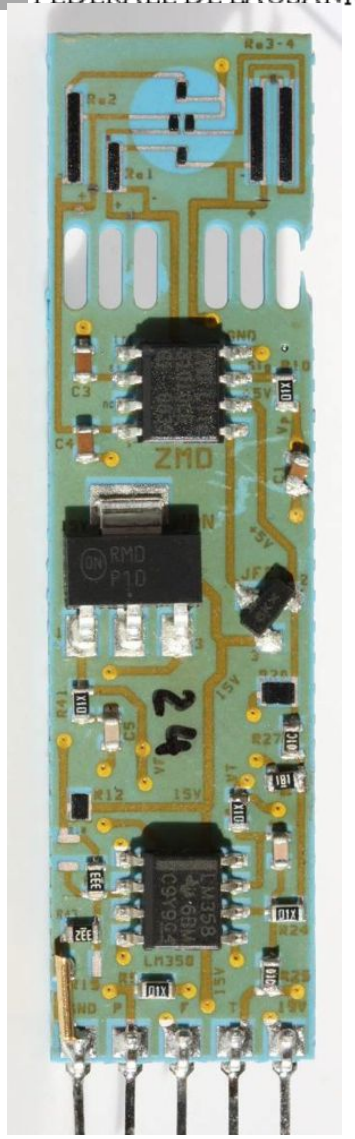
Application: pneumatic industry (diagnostics)

- **air pressure** 0...6 bar
- **air flow** 0...100 NL/min
- **air temperature** 0...100 °C

Integration in LTCC

- **3-D multiphysics** sensing
- …with **integrated electronics**
- …**SMD** mountable by soldering

First presented at Eurosensors 2009, Lausanne (CH)



Multisensor concept for P, T, flow

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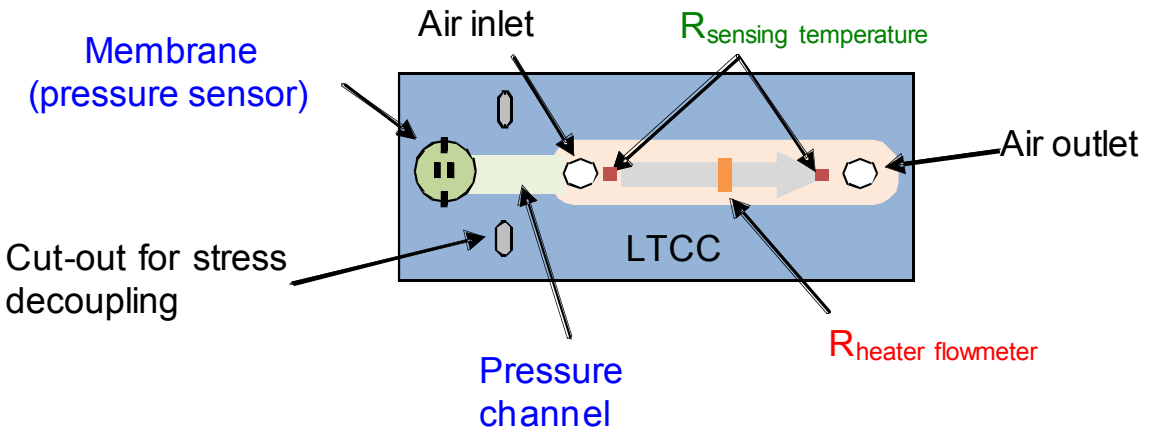
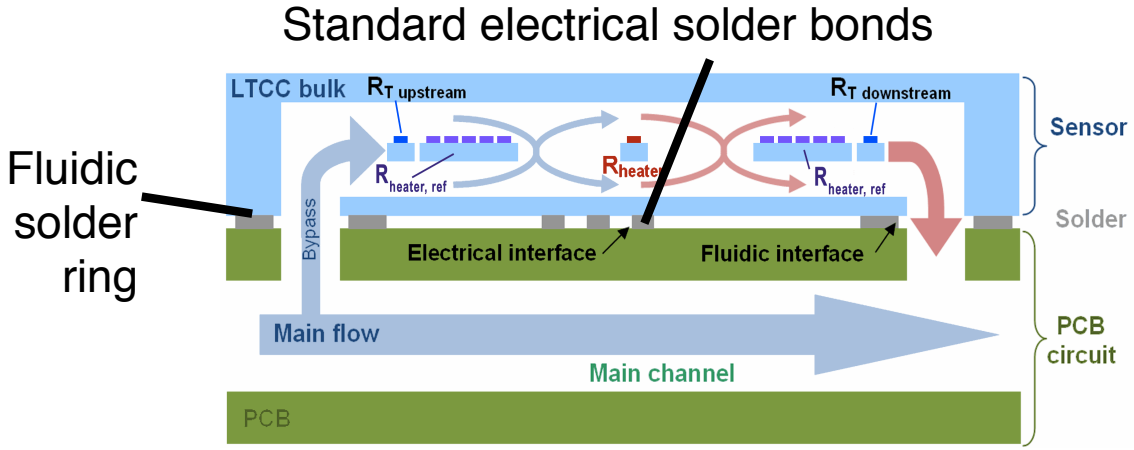
Integrated LTCC sensor with electronics:

- Pressure
- Flow
- Temperature



Sensor properties

- Safe & reliable
- Low-cost
- Easy to integrate - “total SMD" fluidics + electronics



Multisensor overall layout

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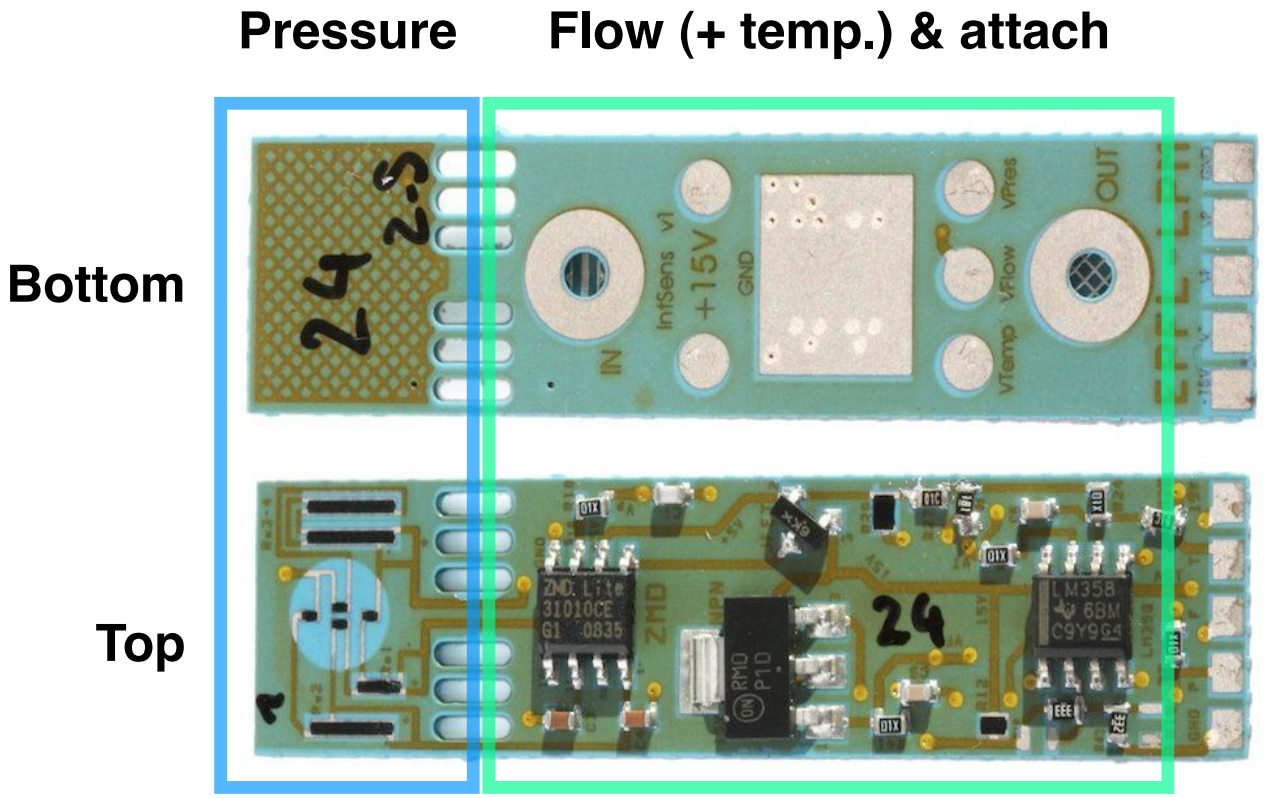
- Long geometry
- SMD pads on flow sensing part (≈insensitive to stresses)
- Stress-sensitive pressure sensing part decoupled



Multisensor - flow-sensing part

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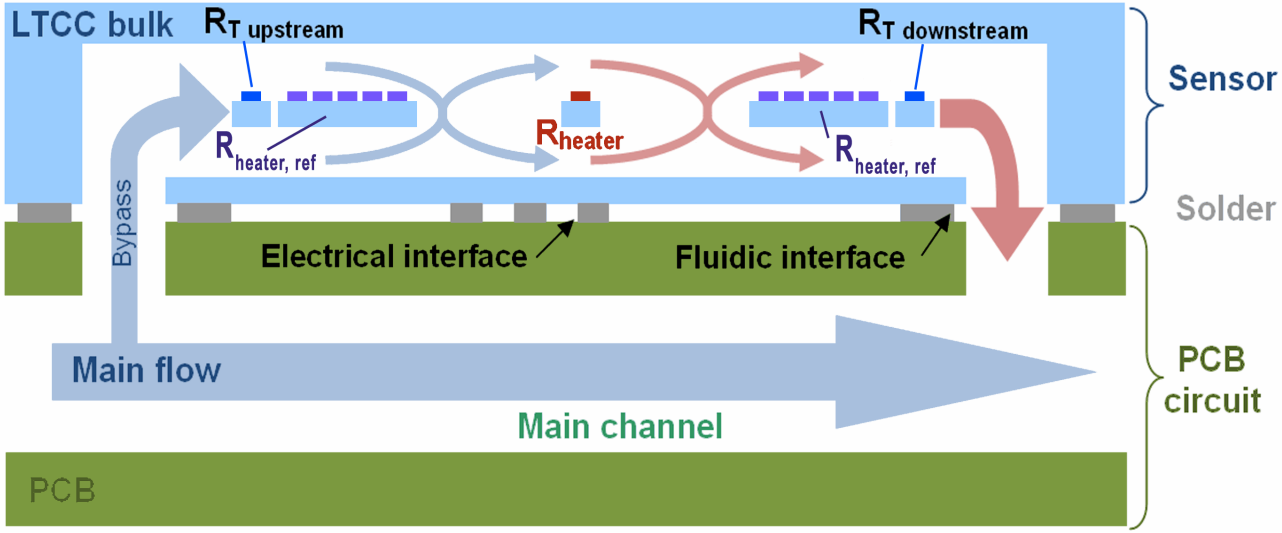
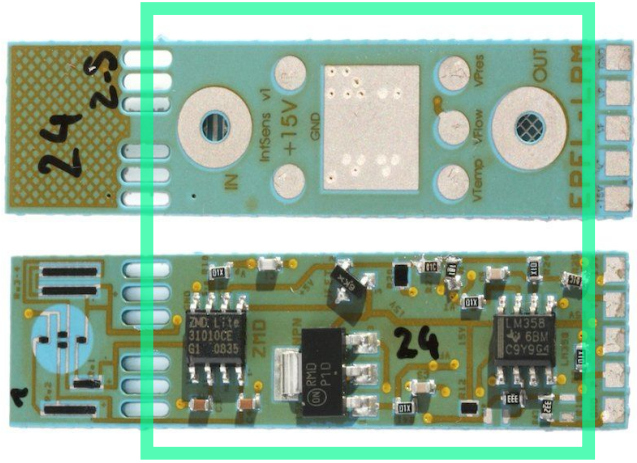
- Measuring + reference thermistors on suspended bridges
- Regulated temperature increment ΔT: measuring vs. reference
- High flows: possible bypass in electrical + fluidic PCB
- Extra passive thermistors to measure temperature





Multisensor - flow & temp. resistor layout

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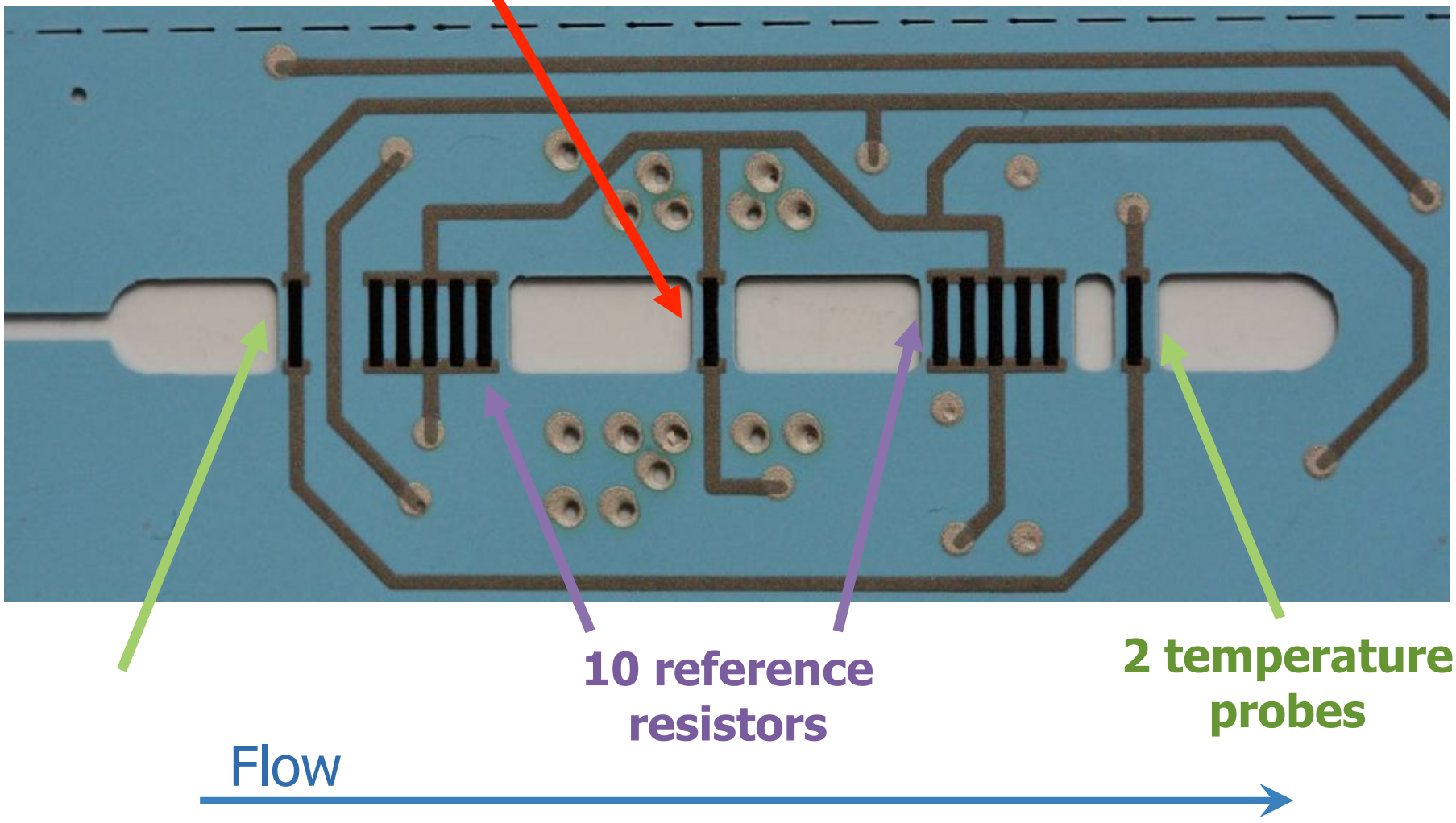
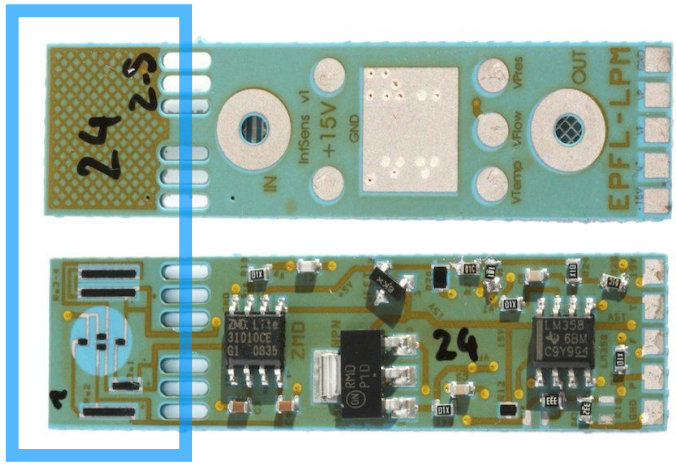
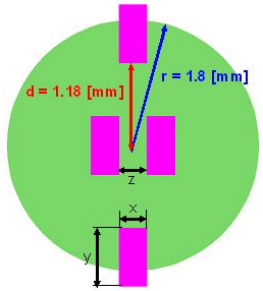
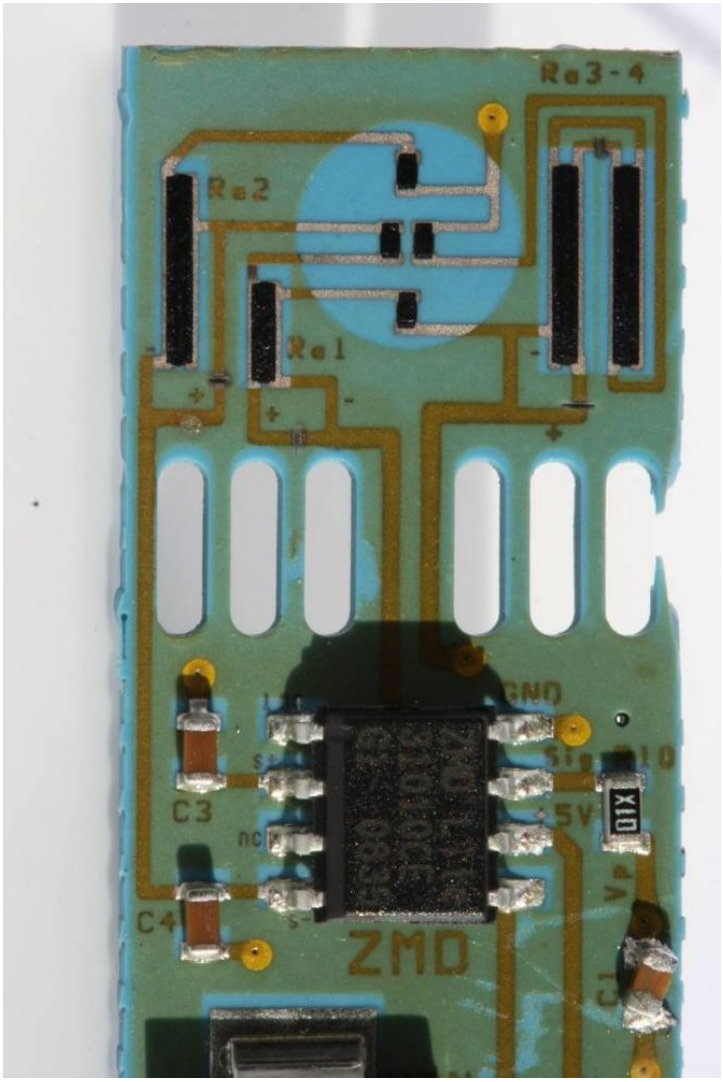


Multisensor structure - pressure



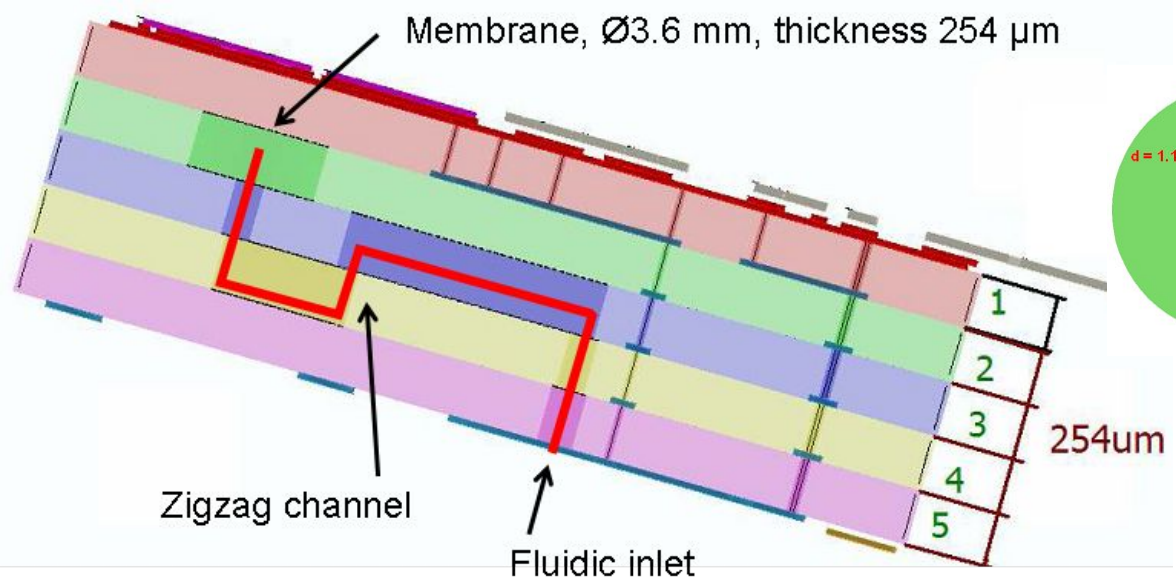


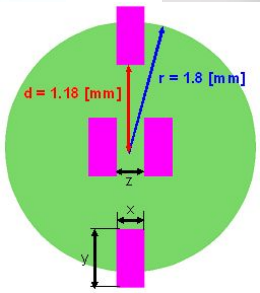
Membrane layout

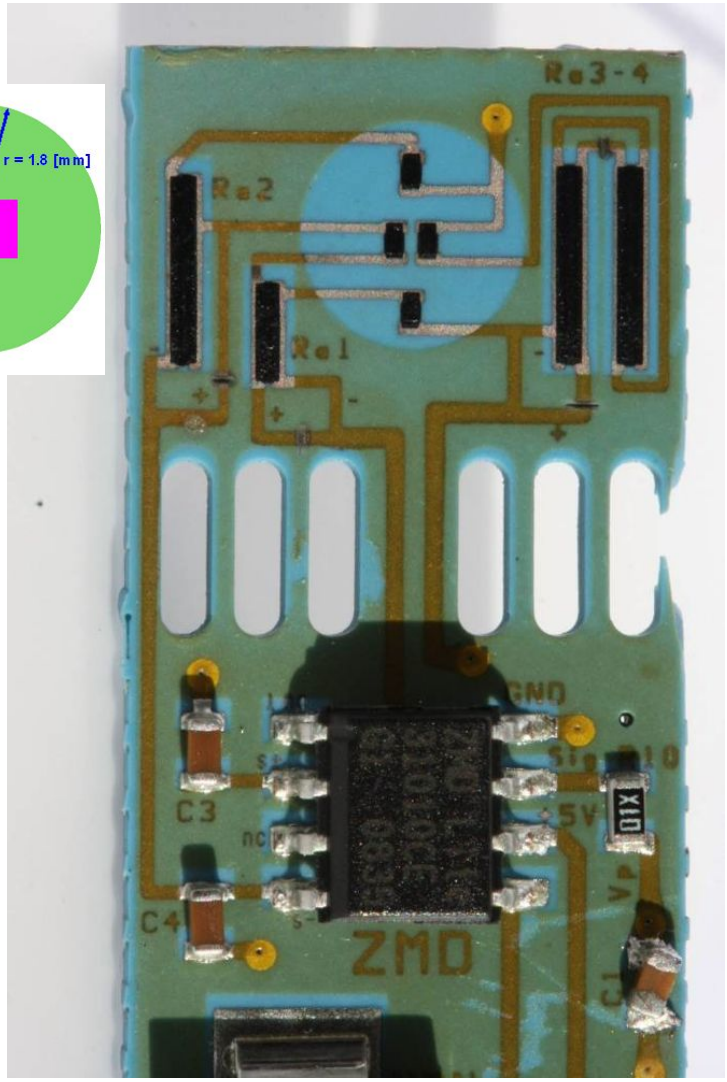


- Nominal pressure: **6 bar**
- **Piezoresistive bridge** on circular membrane
- Pressure path to avoid stress concentration on membrane

Multisensor: pressure sensor







- Nominal pressure: **6 bar**
- **Piezoresistive bridge** on circular membrane
- Pressure path to avoid stress concentration on membrane

Multisensor - pressure conditioning

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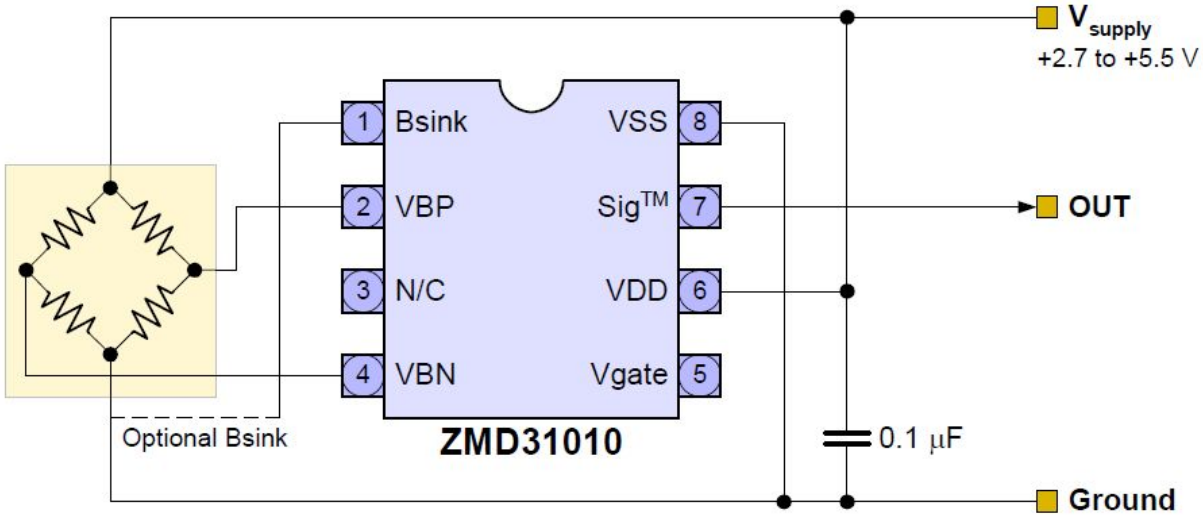
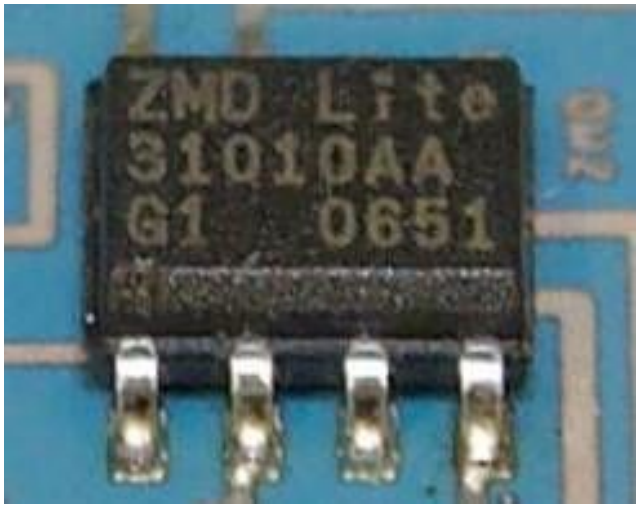
- Easy adjustment of gain/offset

  ⇒ Wheatstone bridge

  ⇒ **programmable integrated conditioner** (*ZMD 31010*)





Multisensor - LTCC stack

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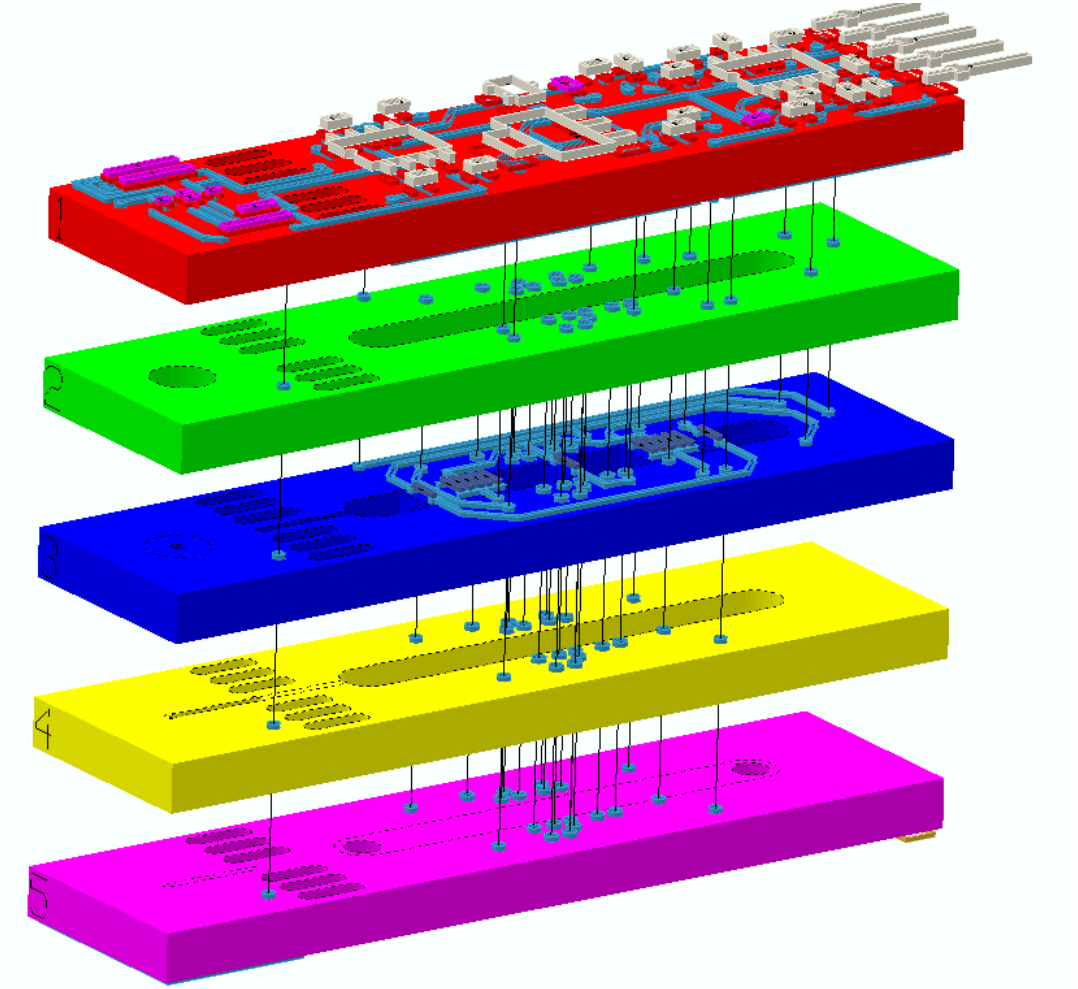
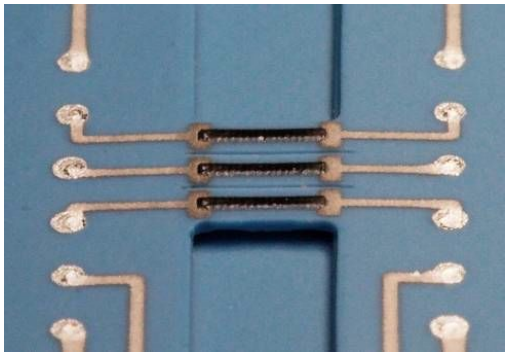
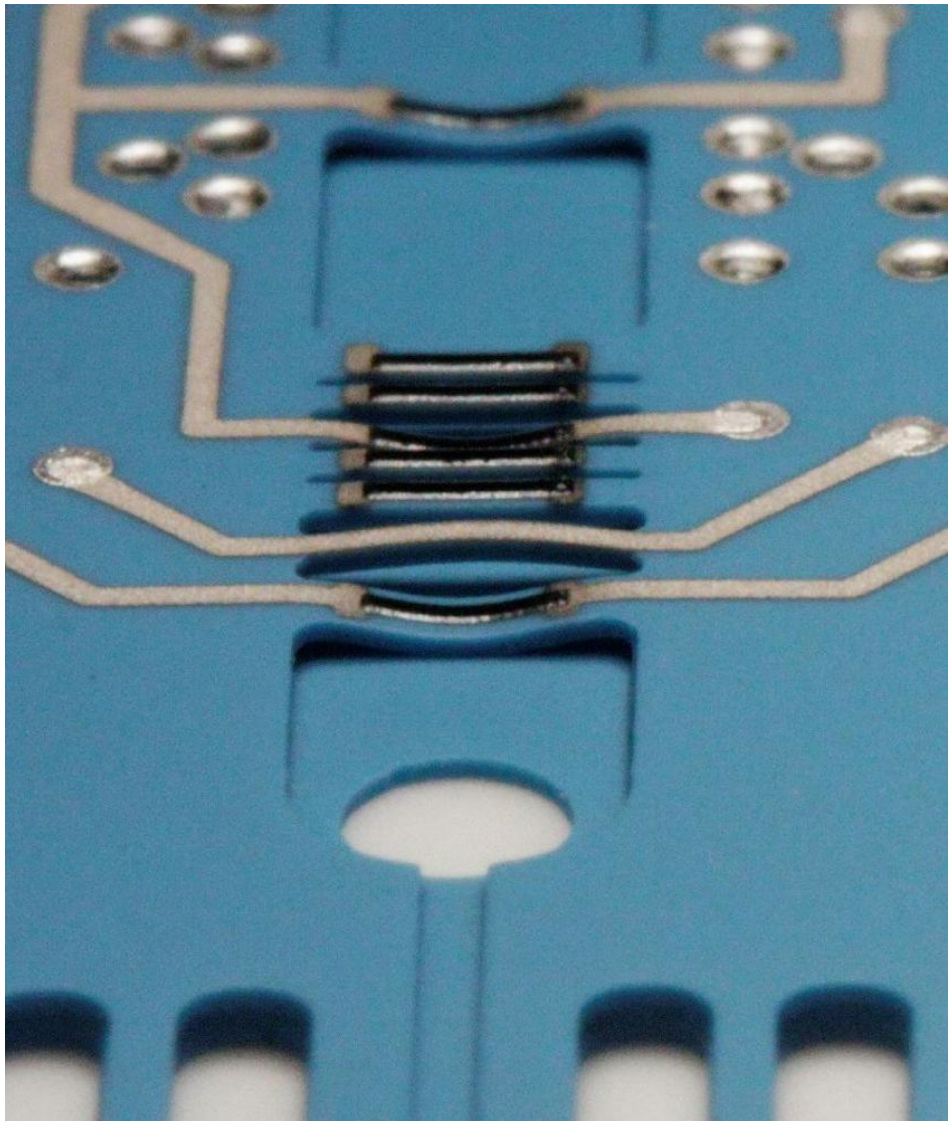
LTCC DuPont 951

- **Vias**
  Ag *DuPont 6141*
- **Conductor tracks**
  Ag:Pd *DuPont 6146*
  Ag *DuPont 6145*
- **Resistors**
  10 kΩ/□ *DuPont 2041*
  PTC *DuPont 5092D*



Multisensor: manufacturing issues





Differential sintering issues between LTCC and pastes
→ **deformations**

⇒ Need adapted layout or sacrificial layers

Meanders & complex circuits

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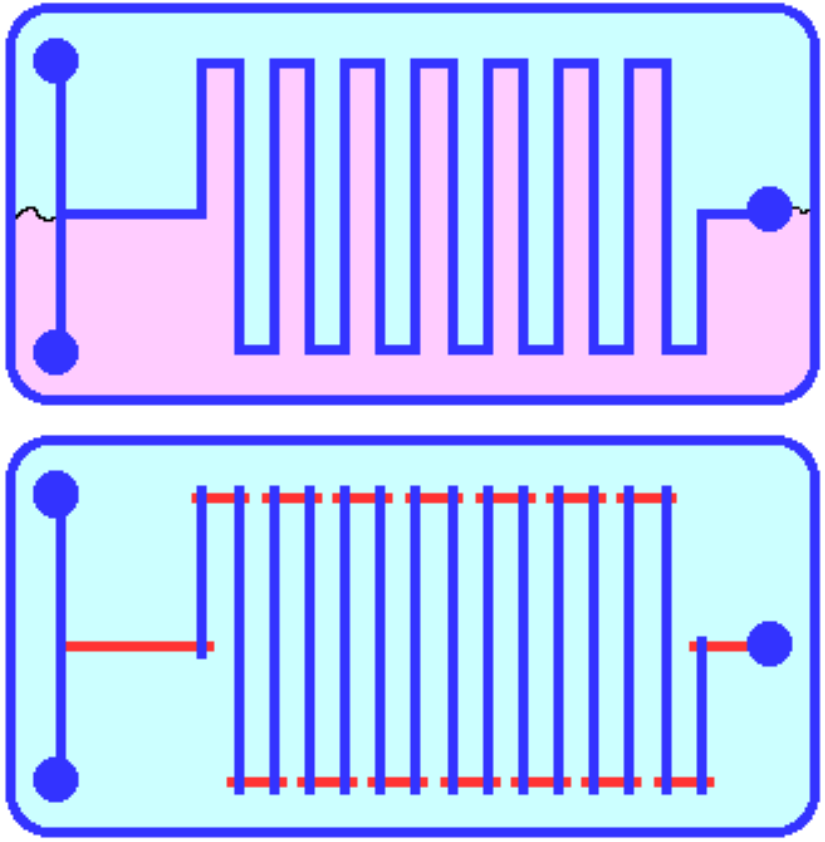
Fabrication of complex LTCC fluidics



- LTCC sheet weak
- Strong risk of clogging

- LTCC sheet stronger
- Less risk of clogging

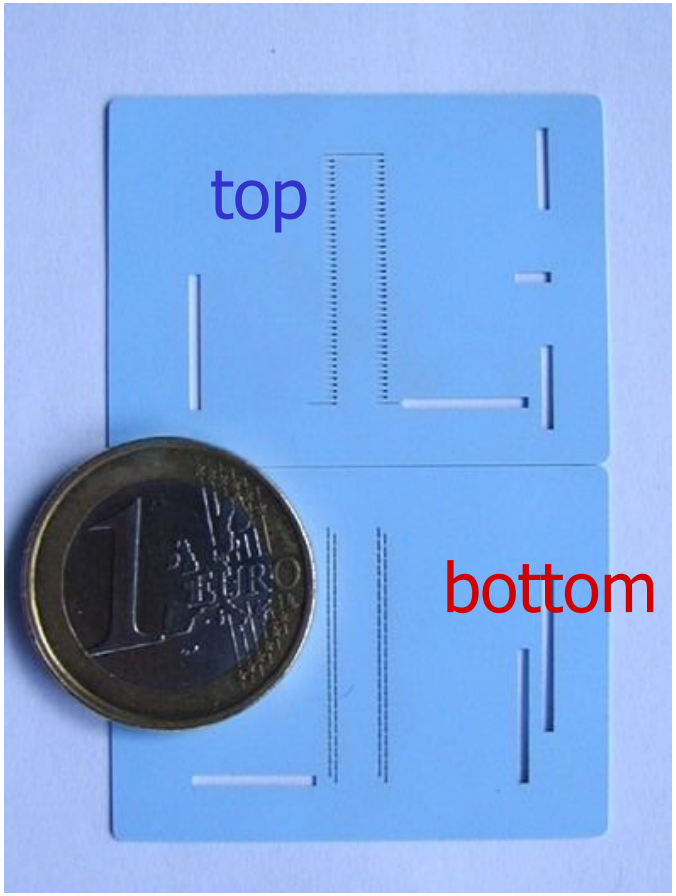
Sheet 1 (top)
Sheet 2 (bottom)

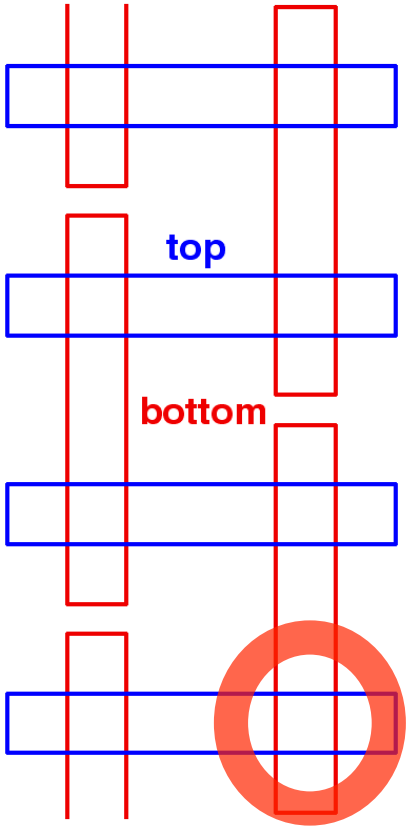
⇒ Avoid long, narrow & windy cuts!

Meanders: zig-zag micromixer

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

V. Mengeaud, EPFL 2002



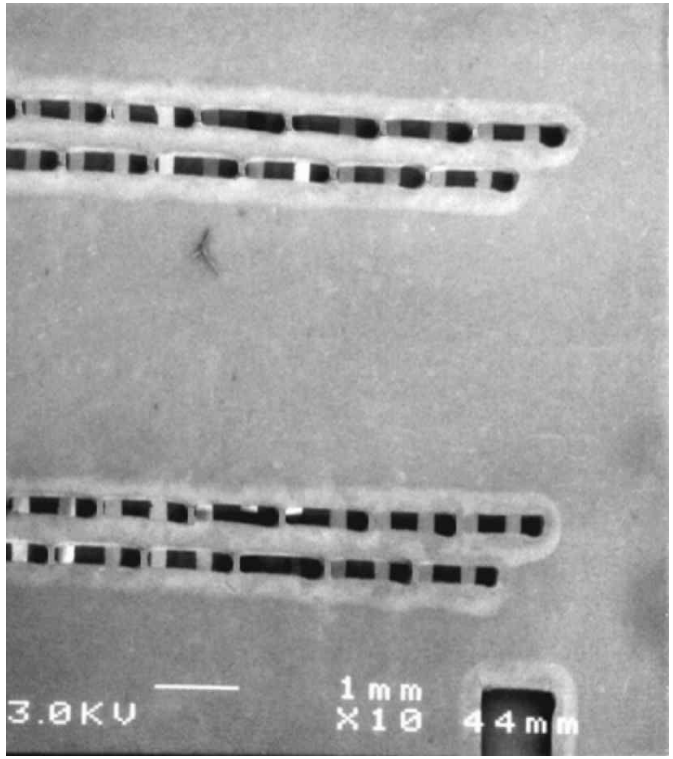


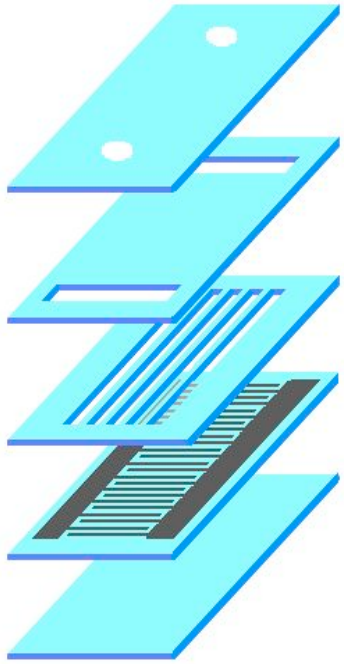
- Two-layer “zig-zag” mixer
- Preserves integrity of LTCC layers
- Extra length: alignment tolerances

Meanders: zig-zag micromixer

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

V. Mengeaud, EPFL 2002



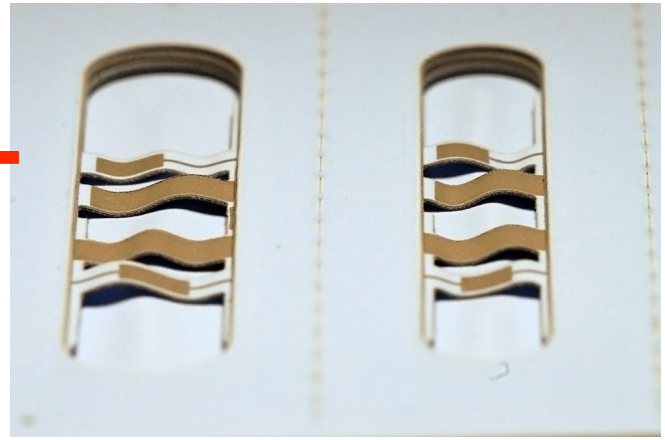


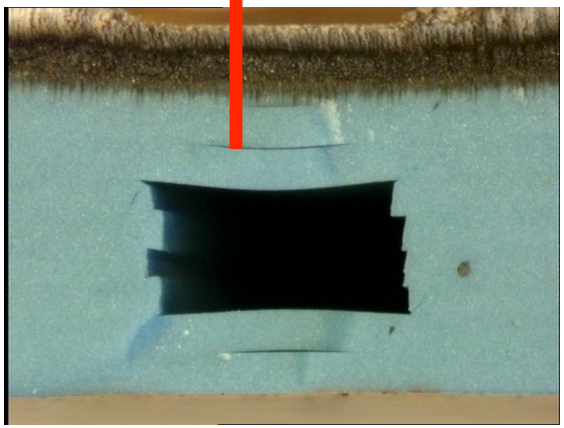
- Two-layer “zig-zag” mixer
- Preserves integrity of LTCC layers
- Extra length: alignment tolerances
- Reliable structure, no clogging
- + electrodes: electrochemical microreactor

Ceramic structuration: lamination issues

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

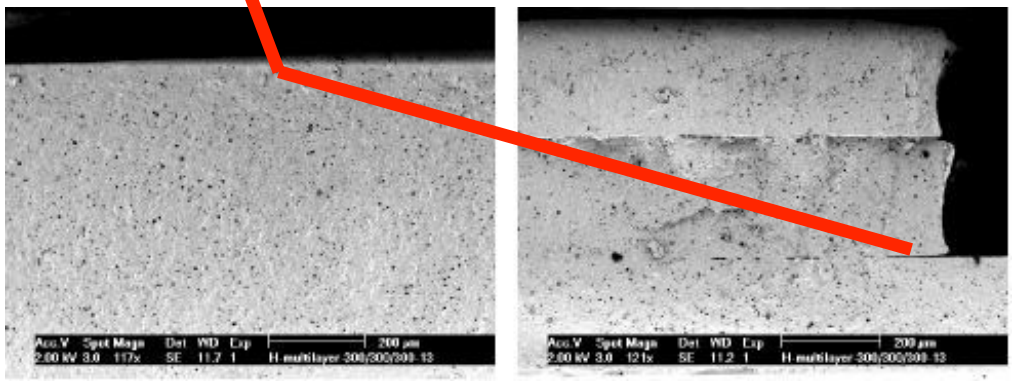
- Standard: ≈70°C 20 MPa
- Deformation of intricate structures
- Lower pressure at edges
- Bonding above & below cavities





Multilayer above & below cavity

Bonding besides a cut-out zone



Basic problem: homogeneous LTCC behaviour

Mechanisms of lamination ≈ tape deformation

Additional possible problems during firing

Outline (3)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

1. Introduction
2. Processing for 3D
3. **Materials formulation**
4. Limitations of LTCC
5. Conclusion & outlook

- **LTCC compatibility**
- **Carbon SVMs**
- **Mineral SVMs**
- **Adhesives for low-pressure lamination**

Lamination: proposed solutions

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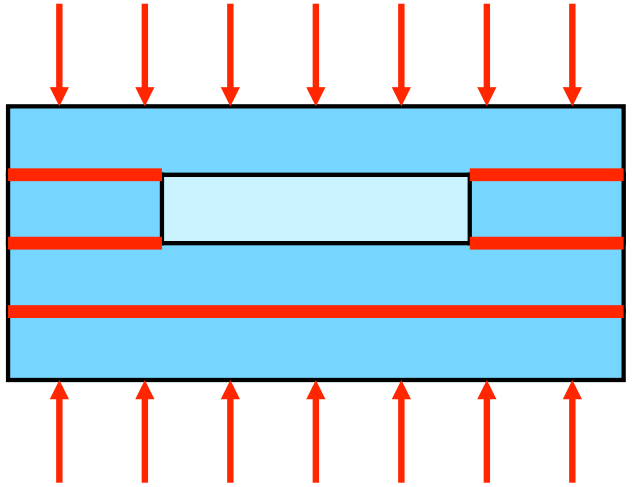
Sacrificial volume materials - SVMs

- Prevent crushing / deformation
- Allow standard high-pressure/-temperature lamination
- Somewhat cumbersome (fill complex features)
- Ensure pressure transfer - good lamination

Low-pressure lamination

- Careful determination of minimal parameters
- "Glues": solvents / thinners / honey / printing vehicles
- Adhesive tapes



Formulation: solvents & LTCC

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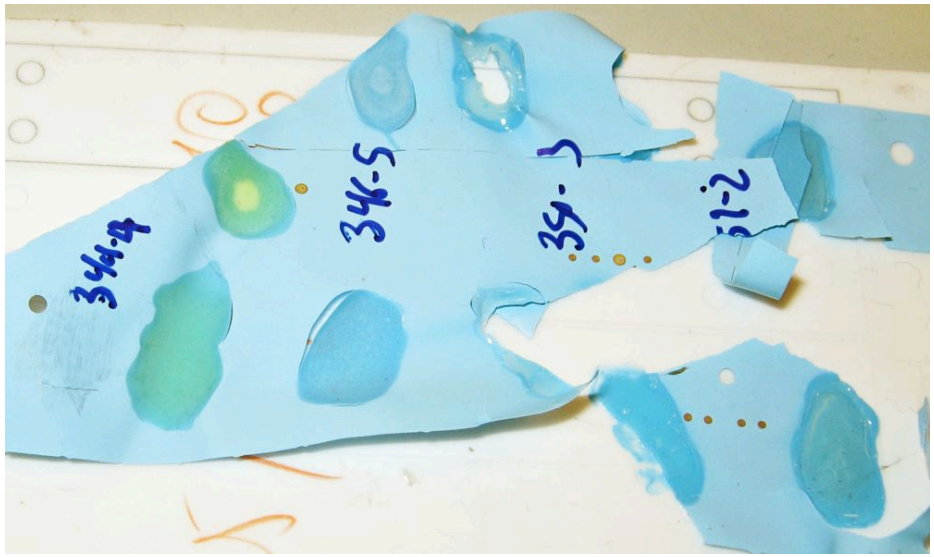
- **Classical - terpineol, texanol**
  - Excessive dissolution of tapes

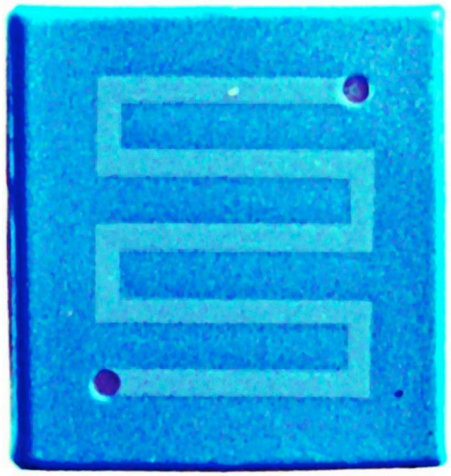


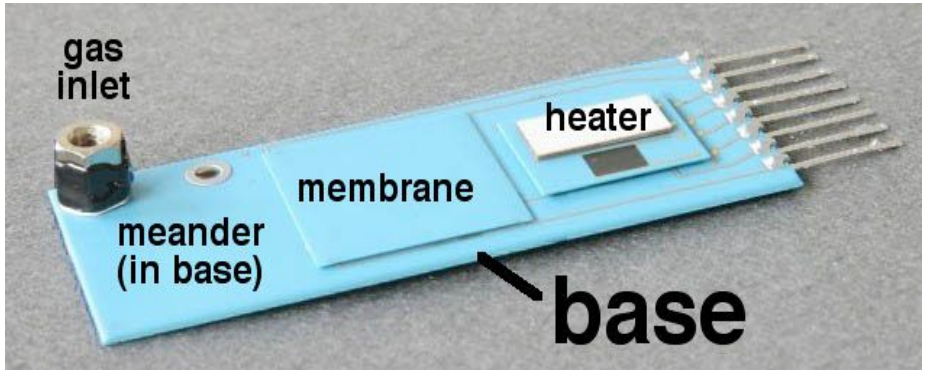
- **Glycols - PG, BG, …**
  - Low attack
  - Not suitable for PVB / EC
  - Suitable for other binders
- **Fatty alcohols**
  - (Cyclo)hexanol: good compromise
  - + tailing solvent: lower volatility
  - Suitable for PVB / EC (esp. with co-solvents / plasticiser)

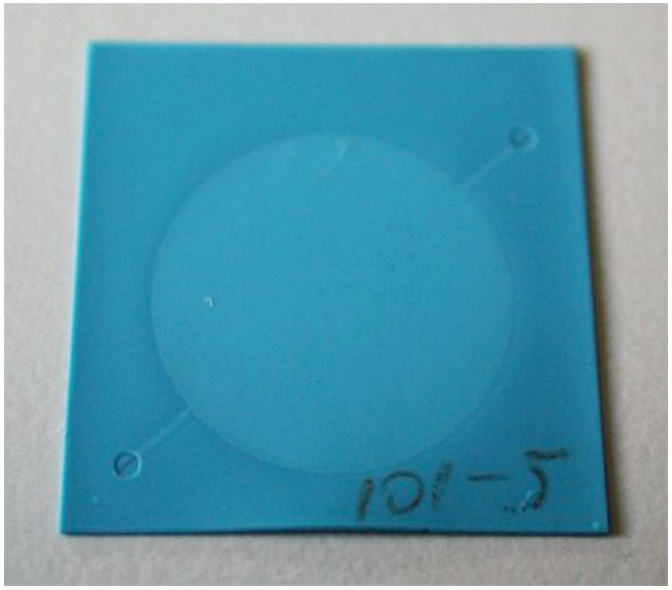
Carbon SVMs - applications

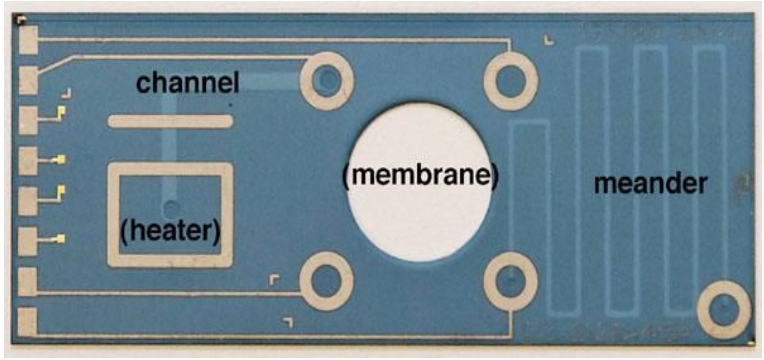
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- Fluidic resistors
- Membranes
- Gas viscosity sensor
- Carbon: membrane & meander









Carbon SVMs - membrane issues

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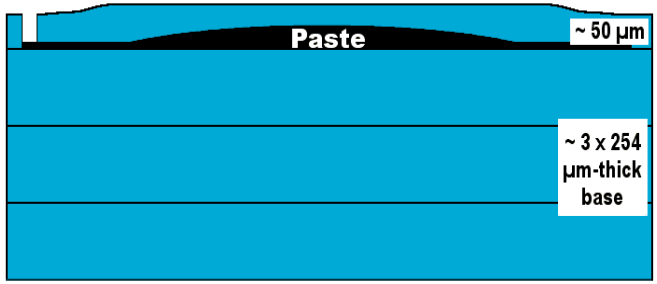
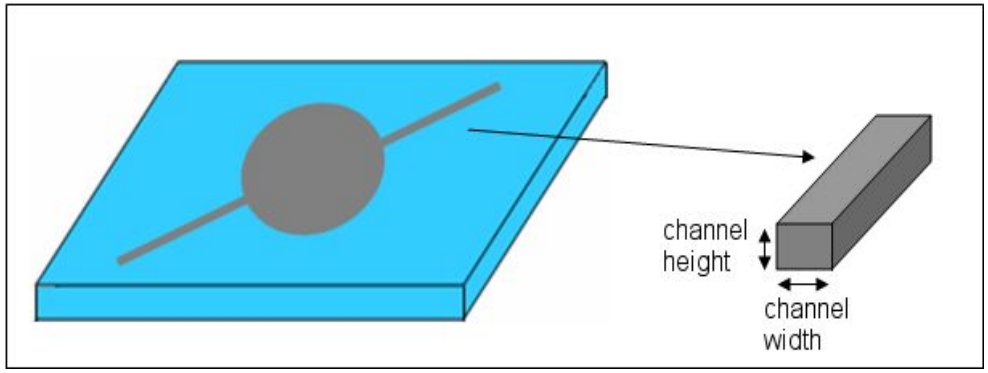
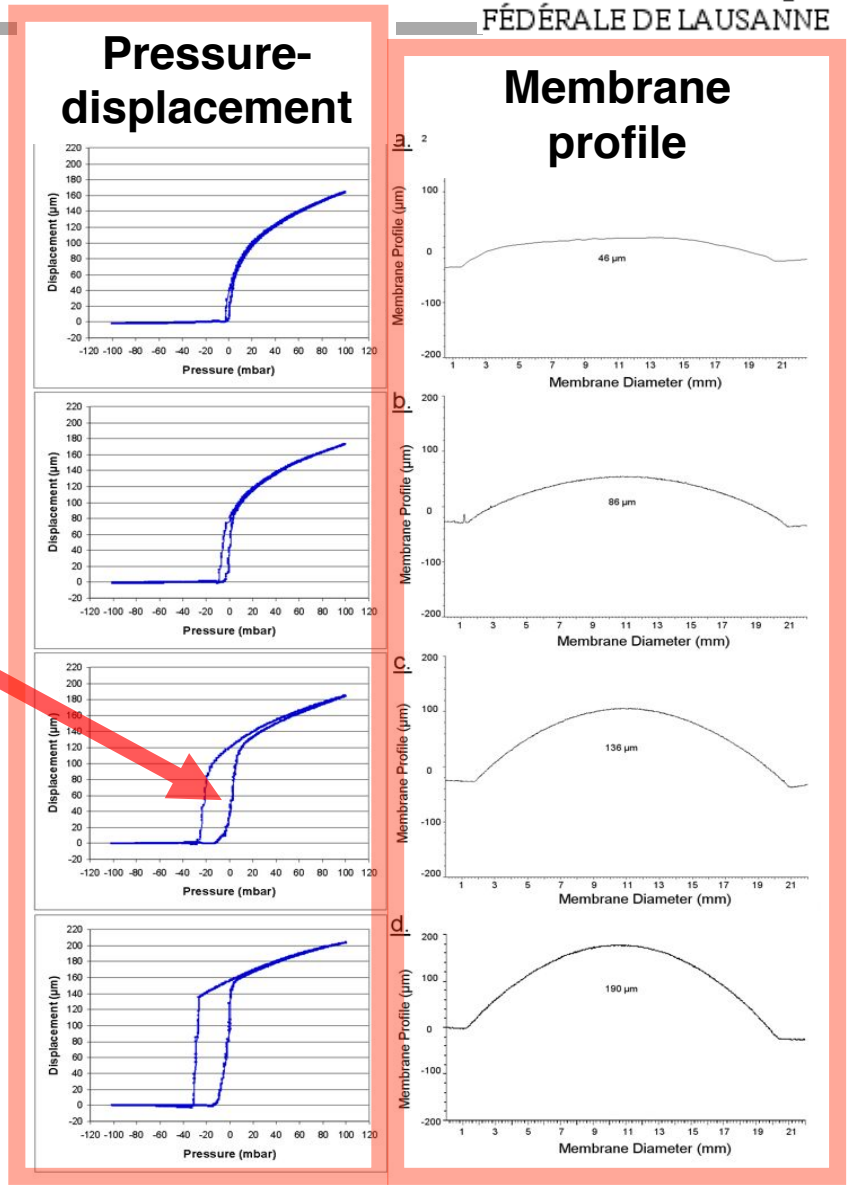
- LTCC membrane: 3x support + 1 thin (50 μm) DP 951 tapes
- Channel width (2:1) & height (2:1)

→ Strong change of properties

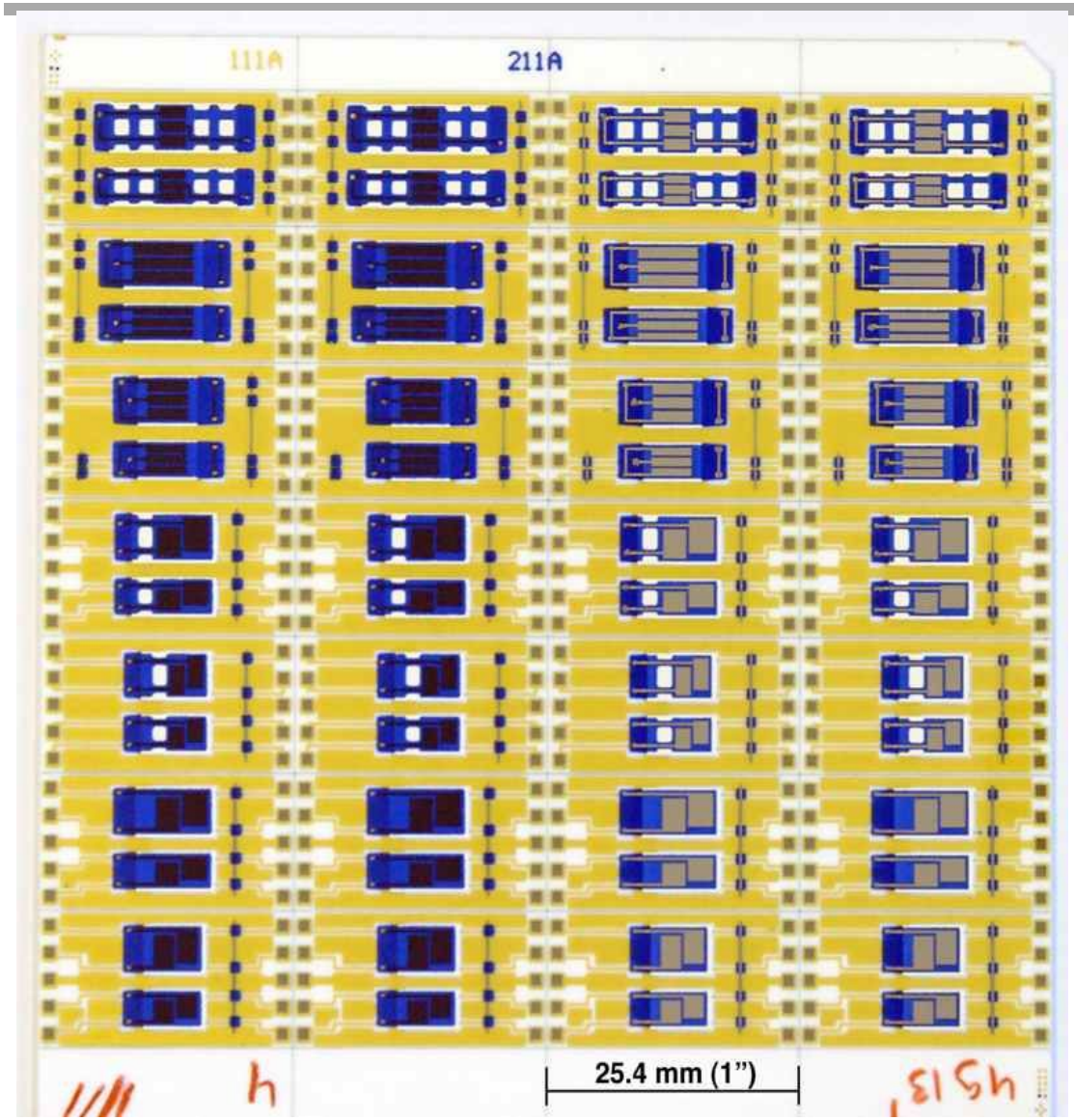




Hysteresis



Mineral SVMs – MgO-based



- Structures for capacitive force sensors / actuators
- Cantilevers or bridges
- Different width
- Plain or structured (cut-outs)

Mineral SVMs – MgO-based

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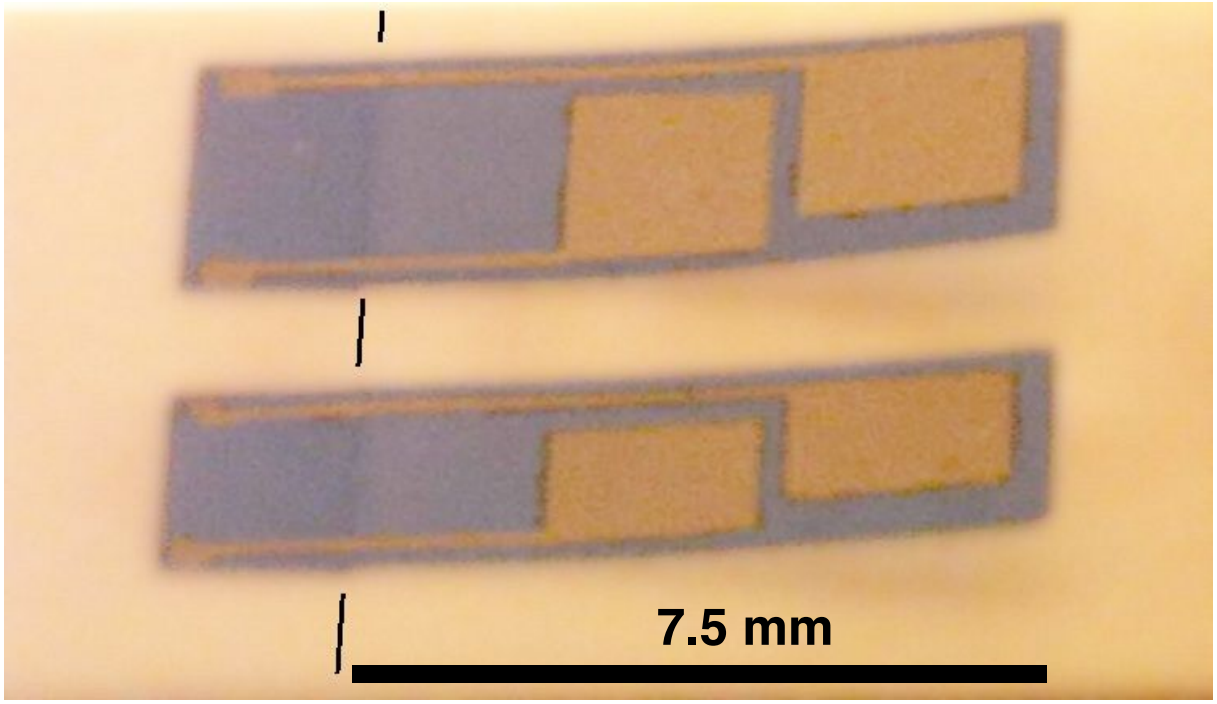
Removal

- Dip into acid (≈ 1 day) @ RT
  - MgO not very reactive
  - "Dead-burned" or additives on surface
  - 10% phosphoric or acetic acid not optimised
- Rinse with tap water
- Neutralise acid with TRIS buffer
- Rinse with deionised water
- Rinse with isopropanol
- Dry @ 60°C in oven

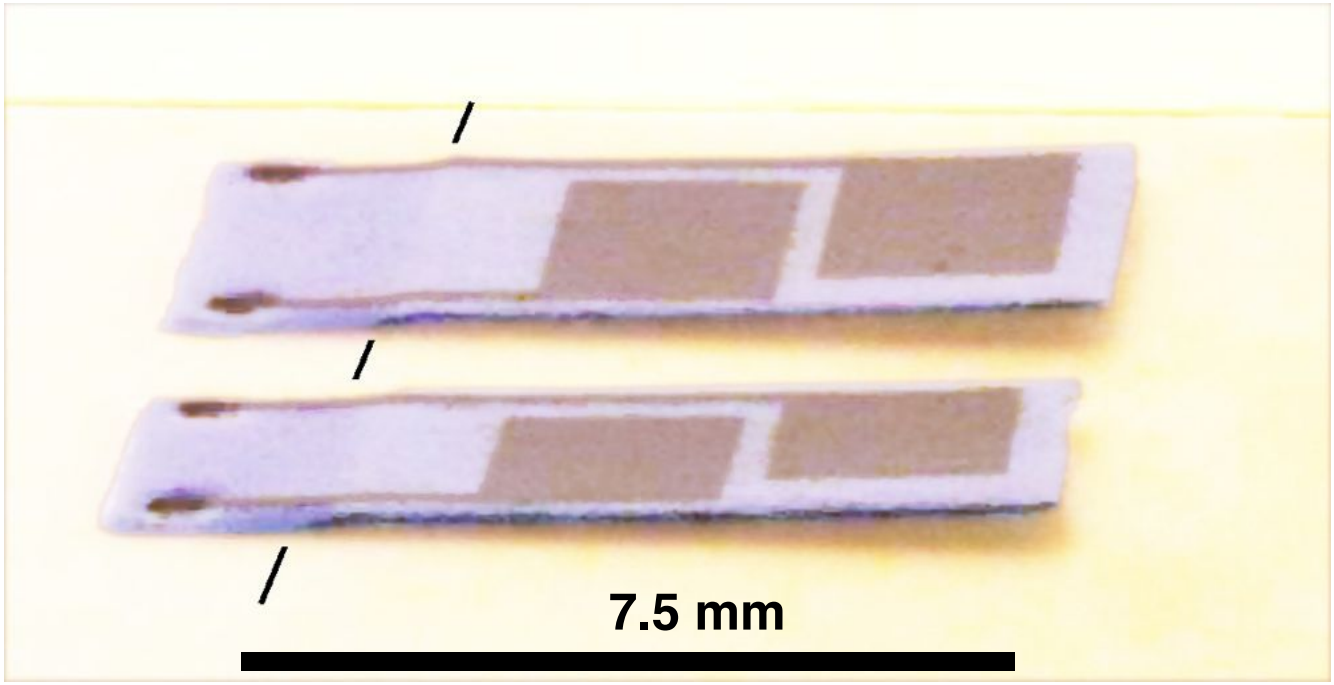
Mineral SVMs – obtained structures

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



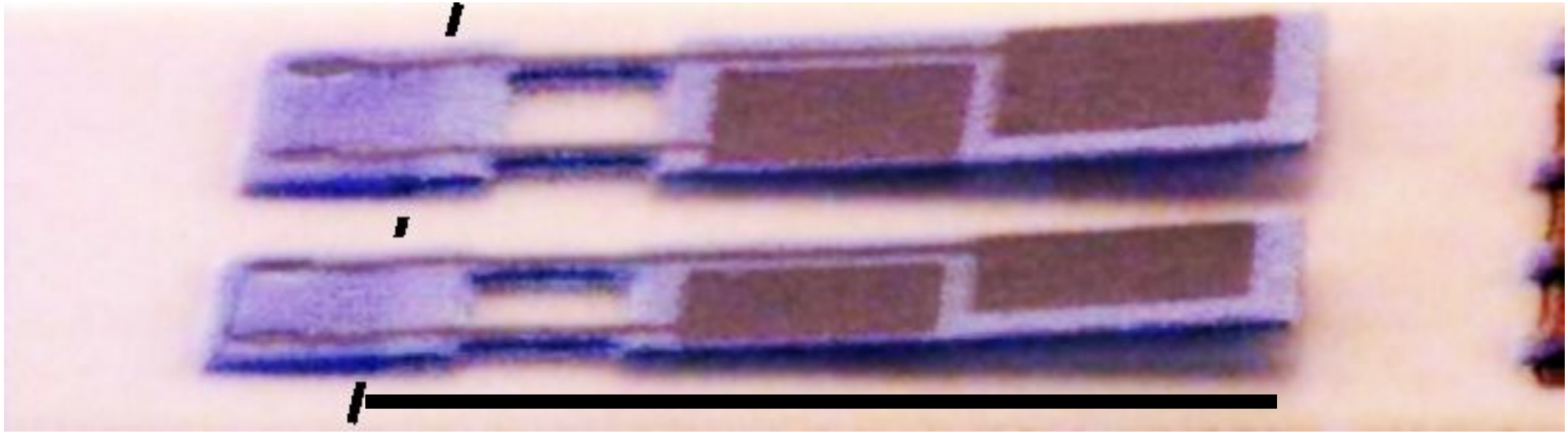
- Plain cantilever : 2 x ESL 4913 + 1 x AgPd ESL 9635B
- Lifting due to built-in strain (TCE mismatch)
  - No lifting was present before etching

Mineral SVMs – obtained structures



- Plain cantilever: 3 x ESL 4904 + 1 x 9535B + 1 x 4904
- Lower lifting due to partial structure compensation

Mineral SVMs – obtained structures



- Structured cantilever: "hinges" to increase flexibility
- Advantage: move weak point away from base-cantilever junction

Adhesives: tested systems

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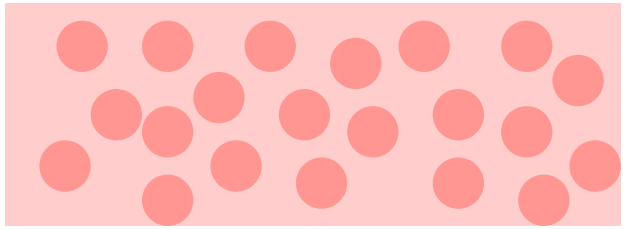
2 alternatives:

- **Solvent-binder-plasticiser**
  - Formulate to dry "just non-tacky"
  - Upon reheating, plasticiser serves as solvent
  - Somewhat progressive solid-liquid transformation (homogeneous glass)

- **Solvent-binder-[plasticiser]-wax**
  - Wax crystallises out @RT: non-tacky
  - Upon reheating, wax acts as a solvent
  - More abrupt solid-liquid transition possible



Adhesives: binders

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- "Common" binders selected
- PVB, PxMA or EC: used in tapes & pastes
- Hansen solubility parameters (give an idea…)
- Other binders possible (HPC, PVP, …)

Binder	δ_d [MPa$^{0.5}$]	δ_p [MPa$^{0.5}$]	δ_h [MPa$^{0.5}$]	R [MPa$^{0.5}$]	**Note**
PVB (20% OH)	18.6	4.4	13.0	10.6	Solubility in polar solvant with H bonding (alcohols, acohol-ethers, alcohol-esters)
PMMA	18.6	10.5	7.5	8.6	*Solubility in esters, ketones, alcohol-ethers, acohol-esters*
EC	17.1	7.3	9.7	9.0	Intermediate btw. PMMA & PVB In practice very easy to solubilise in a wide range of modestly polar solvents

Lamination quality & distortion

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

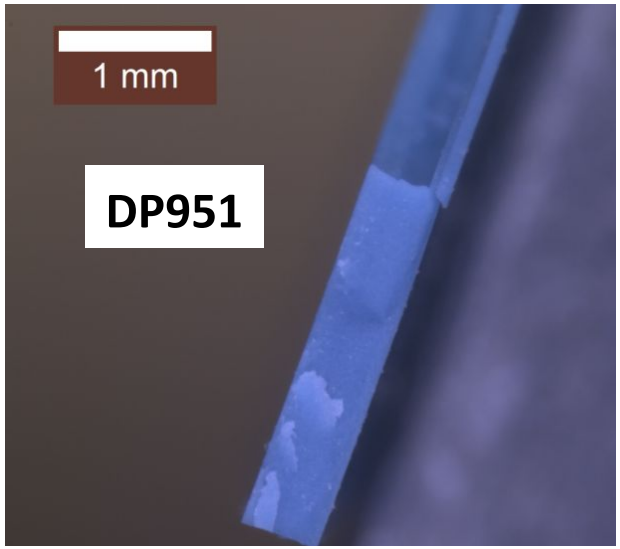
- Simple ø5 mm membranes
- Tapes: DP 951 or Her HL2000
- Good bonding & low distorsion @60°C

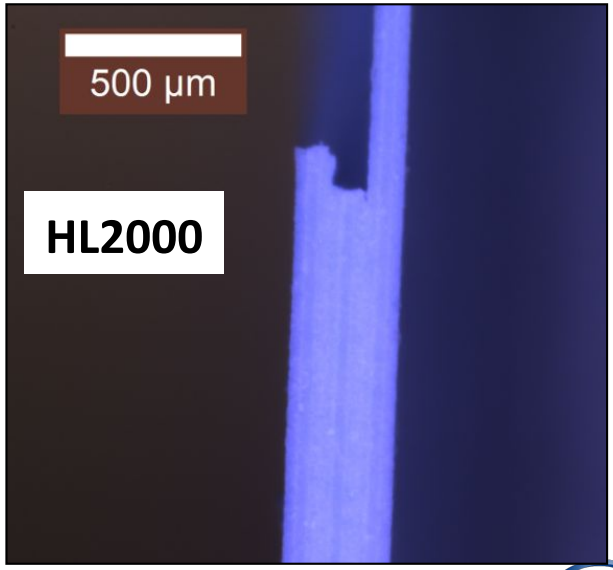
DP951

Membrane (µm)		1.94 MPa		3.88 MPa		7.75 MPa	
Glue	LTCC	fired quality		fired quality		fired quality	
#344-5	1st layer	7	dense	7	dense	4	dense
#346-6	1st layer	12	dense	6	dense	10	dense
#362-4	1st layer	6	dense	11	dense	7	dense
#363-2	1st layer	11	dense	6	dense	3	dense

HL2000

Profilometer results		**1.94 MPa**		**3.88 MPa**		**7.75 MPa**	
Glue	LTCC	fired quality		fired quality		fired quality	
#346-6	1st layer	8	dense	10	dense	15	dense
#362-4	1st layer	9	dense	5	little crack	13	dense
#363-2	1st layer	10	little crack	13	dense	12	dense



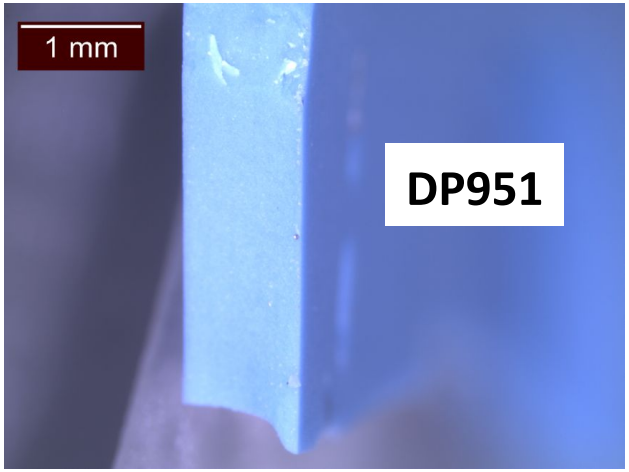


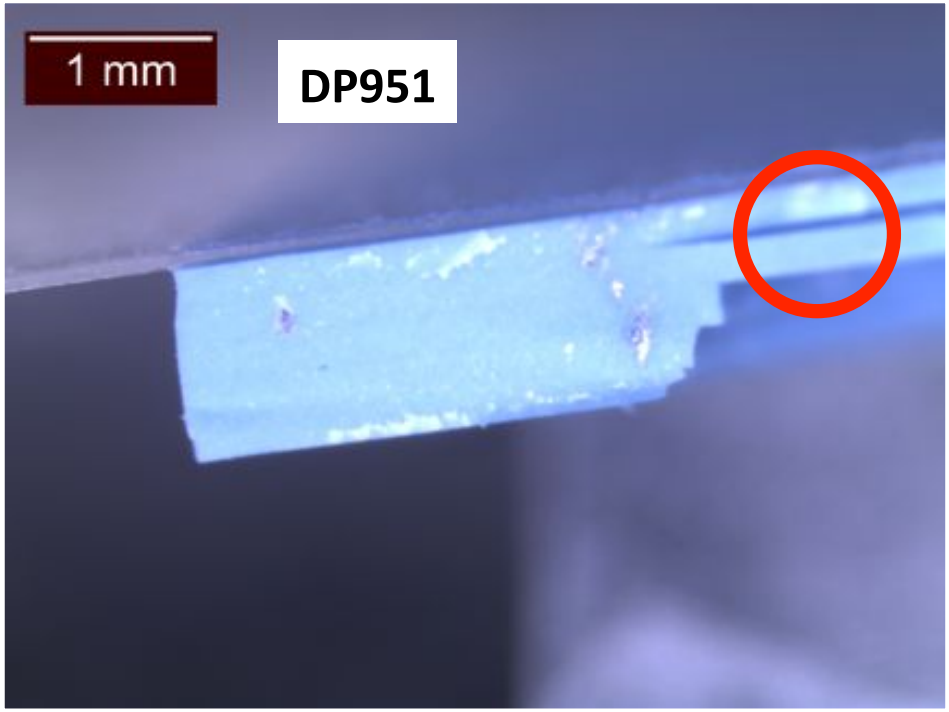
MIDEM

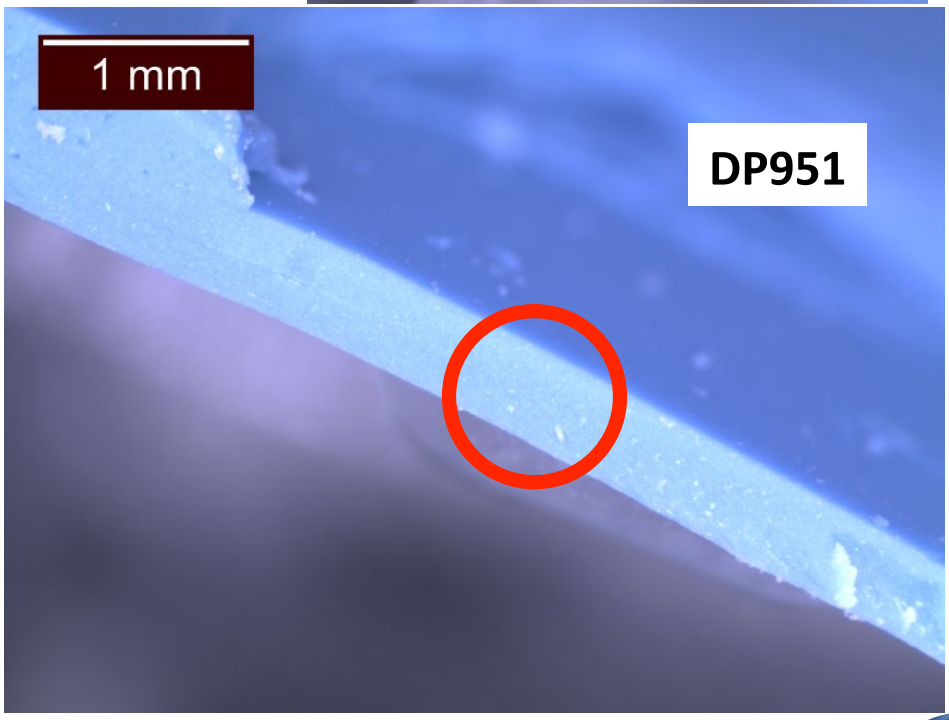
Lamination quality & distortion

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- Body mostly OK
- Double membrane layer difficult (no pressure)
  - More glue: lamination OK, but deforms more upon firing







Outline (4)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

1. Introduction
2. Processing for 3D
3. Materials formulation
4. **Conclusion & outlook**

Conclusions & outlook

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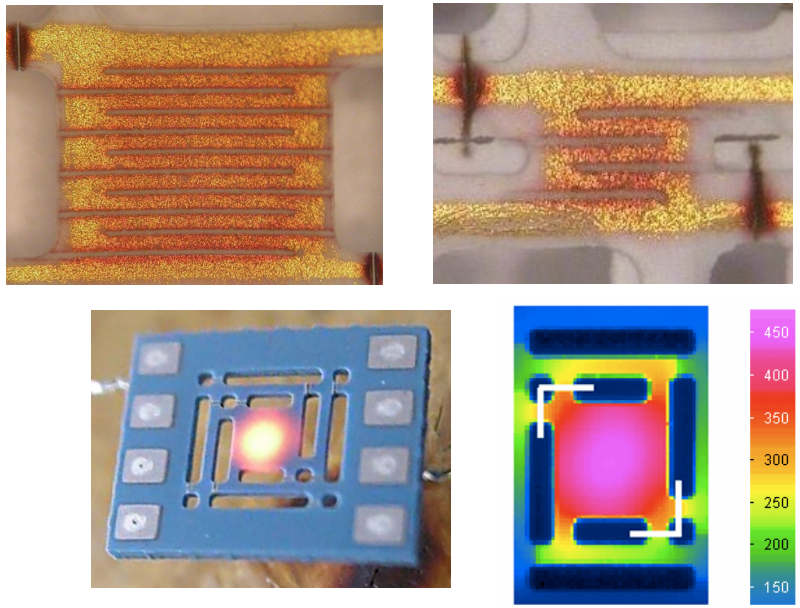
Thermal & fluidic structures

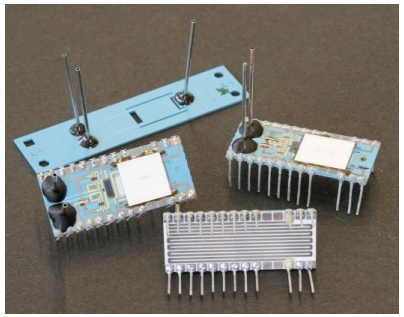
- Wide range of achieved structures, **BUT:**
- 3D structuration not trivial
- Techniques to be adapted to application
- Materials compatibility issues

Outlook

- More developments needed for better standardisation
- Long-term characterisation of reliability & stability



LTCC *μ*-hotplates
2010 Barras



LTCC *μ*-reactor
2005 Willigens
2006 Maeder

Questions?

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Thank you for your attention!

Formulation: compatibility

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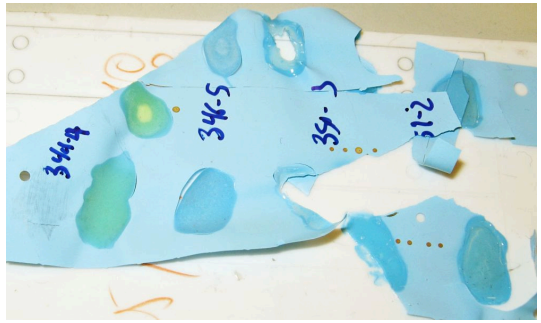
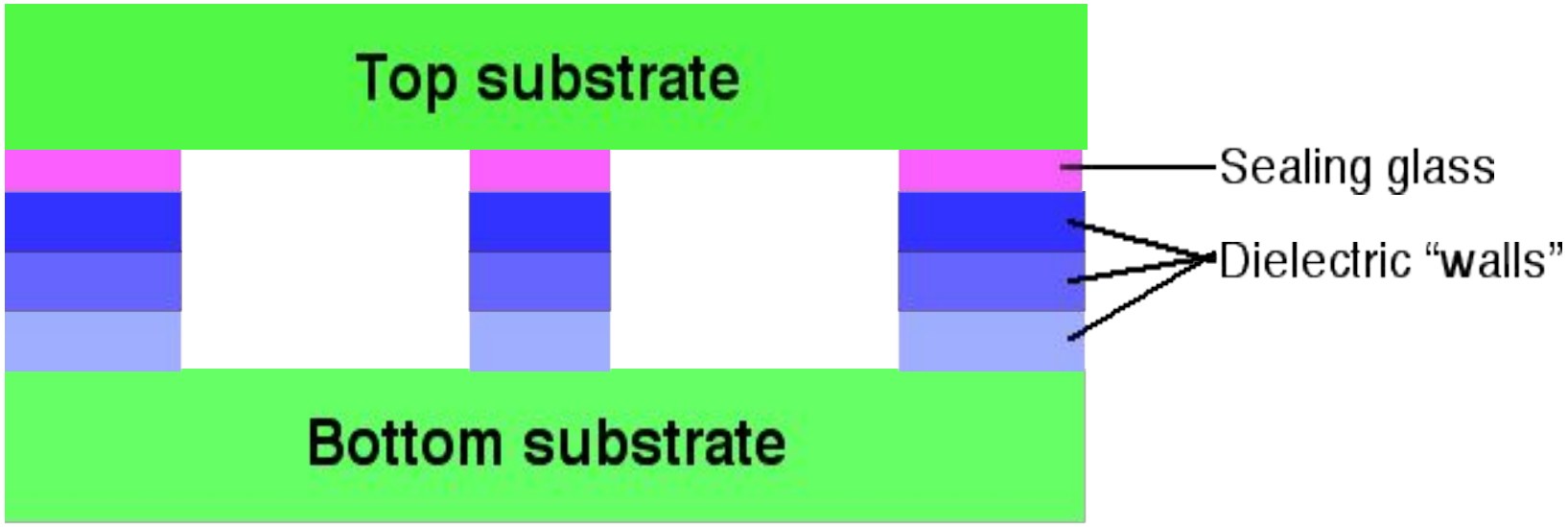
- **Tape binders (typ.):**
  - Acrylics: PMMA, PEMA, PBMA, …
  - Polyvinylbutyral (PVB)
  - > Sensitive to polar organic solvents



- **Screen emulsions (typ.):**
  - Polyvinylalcohol (PVA, PVOH)
  - > Sensitive to water only

- **Avoid tape dissolution:**
  - Low solvent amount: high-solids
  - Solubility parameter mismatch
  - Balance volatility: screenability vs. persistence - attack
    - In this respect, methods compatible with volatile solvent better (spray, inkjet, dipping, …)

Thick-film fluidics: glass sealing



- Alumina bottom substrate
- Walls built-up by thick-film dielectric
- Final layer = sealing glass
- Glass sealing of top substrate
- Max practical height: ca. 100 µm
- Simple circuits (1 layer)

μ-SOFC system principle

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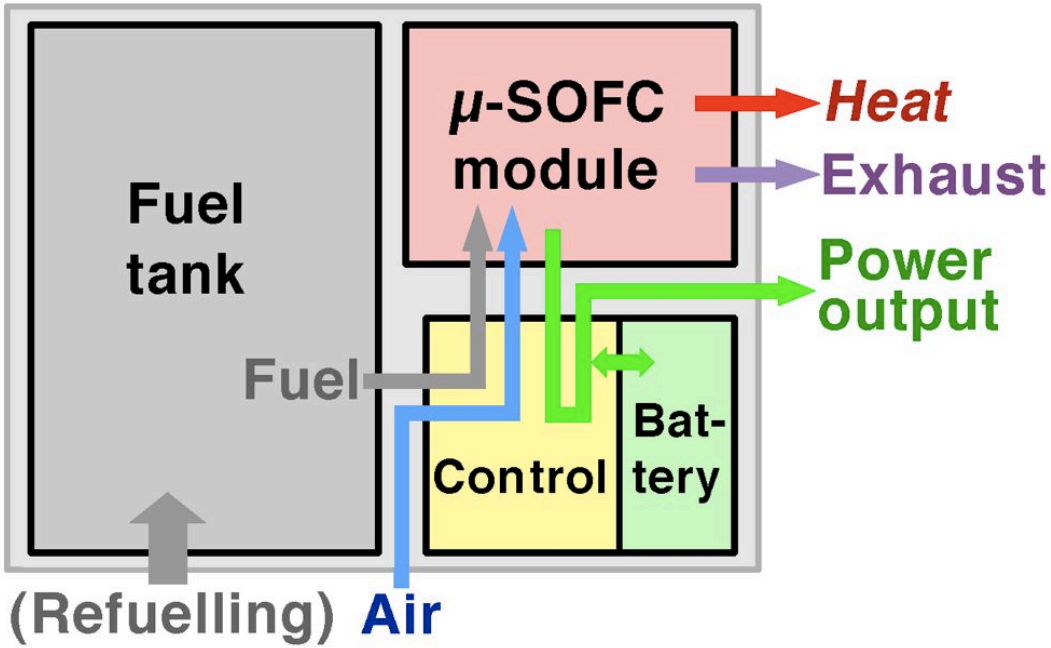
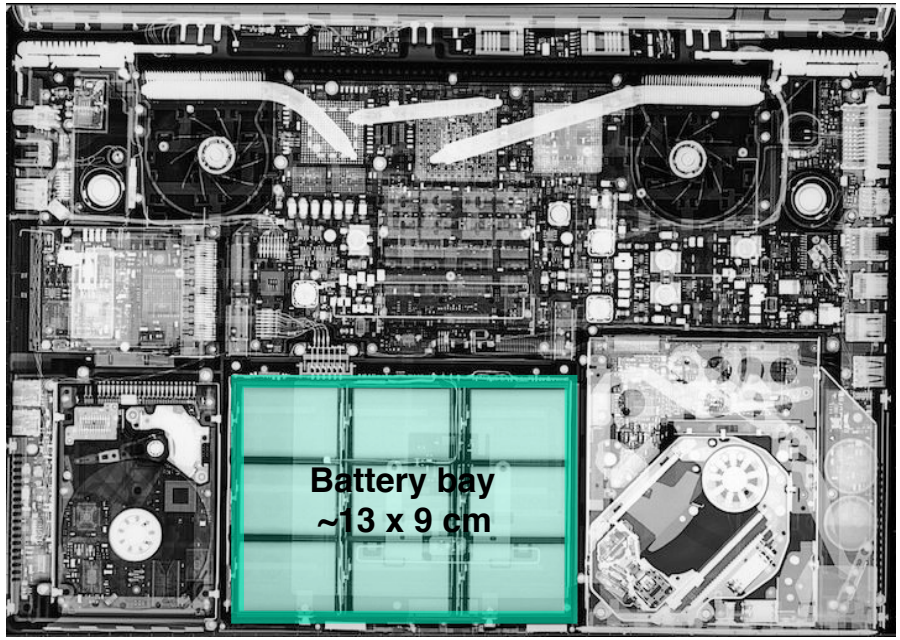
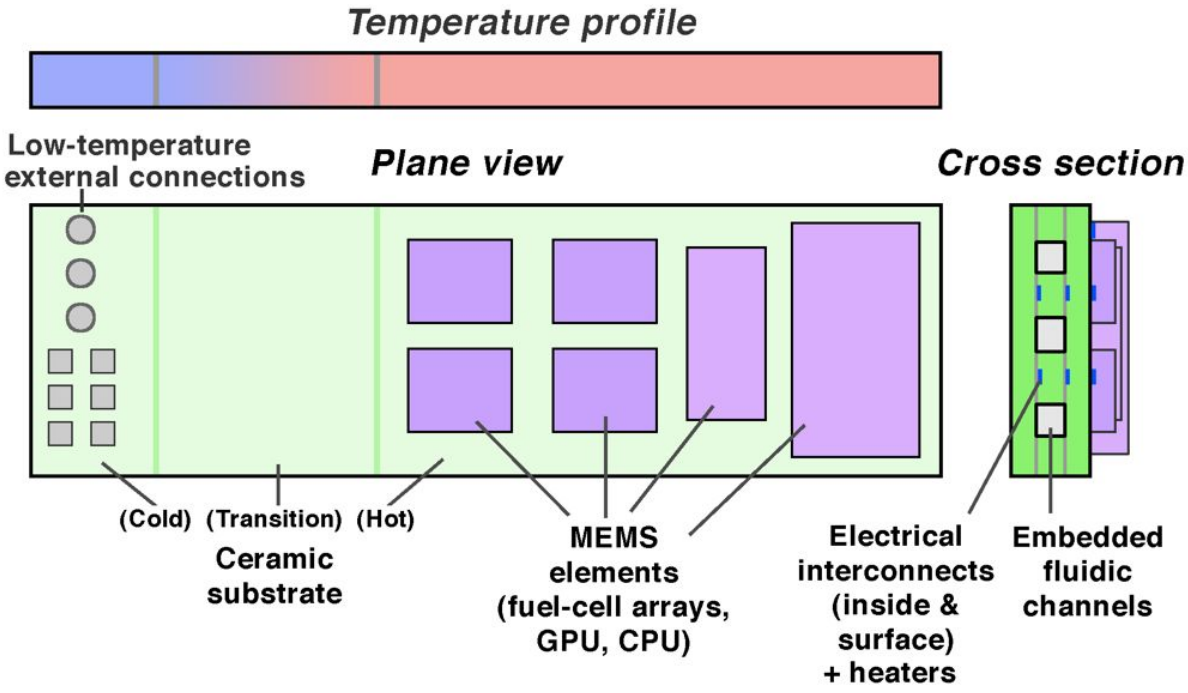
- Integration into a single, compact module
- Can replace battery bay in portable electronics





LTCC μ-SOFC module concept

- Simple "stick" structure
- Facile thermal & mechanical decoupling
- External (electrical & fluidic) connections at low temperature
- Integration of fluidics & possibly gas processing



LTCC μ-SOFC module packaging concept

LTCC μ-SOFC module concept

- Simple "stick" structure
- Facile thermal & mechanical decoupling
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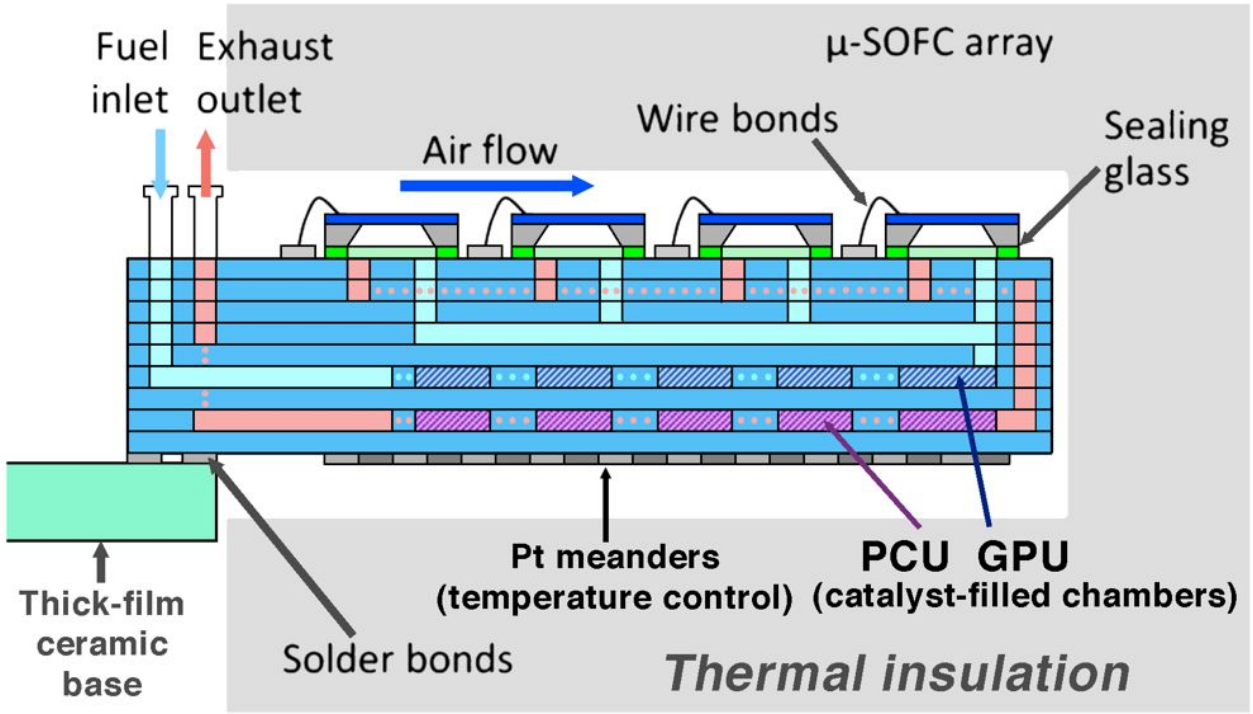

LTCC μ-SOFC module

PCU = post-combustor
GPU = reformer

Thermal decoupling

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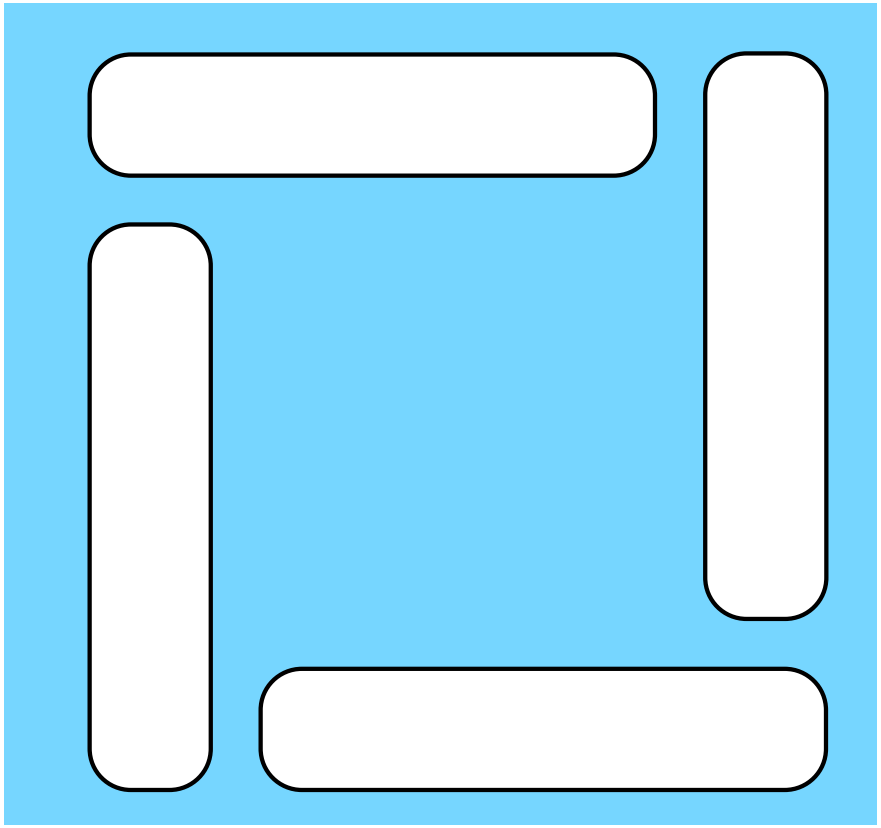
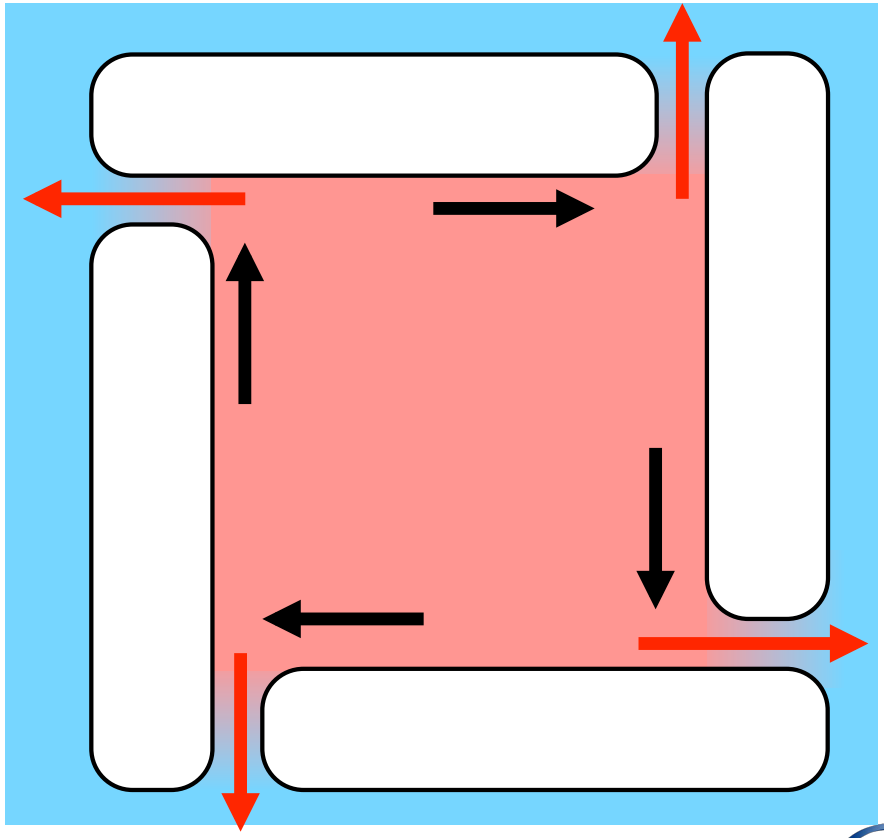
- Achieve thermal + mechanical decoupling
  - Free mechanical displacements (→) due do thermal expansion
  - Minimise thermal loss paths (→)
  - Issues: processability - complete post-shaping not practical





Carbon sacrificial layers - process

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- Print [fire] sacrificial paste onto LTCC / ceramic substrate
- Laminate (LTCC) / print (ceramic) top layer
- Fire structure in air / O_2, OR:
- Fire structure in neutral gas & oxidise later
- Post-processing